AD NUMBER	
AD021330	
CLASSIFICATION CHANGES	
TO:	unclassified
FROM:	confidential
LIMITATION CHANGES	
TO:	Approved for public release; distribution is unlimited.
FROM:	Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; 13 APR 1953. Other requests shall be referred to Naval Ordnance Lab., White Oak, MD.
AUTHORITY	
	30 Apr 1965, DoDD 5200.10; USNOL ltr, 29 Aug 1974

CONFIDENTIAL

NAVORD REPORT 2784

AN INVESTIGATION OF SOME PROPERTIES OF COLD CATHODE DIODES

13 APRIL 1953

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

CONFIDENTIAL
SECURITY INFORMATION

AN INVESTIGATION OF SOME PROPERTIES OF COLD CATHODE DIODES

Prepared by:

Julius I. Bowen

ABSTRACT: Some properties of cold cathode diodes manufactured by the General Electric Company for use in the XR-8 Fuze circuit have been examined. Tests have been conducted on breakdown voltage characteristics of the diodes using a variety of test methods, and the effects of repeated breakdowns examined. Energy transfer characteristics of the diodes have been studied, with emphasis on the effect of the magnitude of the applied voltage, and also the dynamic voltage drop characteristics. In the course of the experiments a new test set for measuring breakdown voltage, the Dynamic Breakdown Voltage Tester, has been introduced with significant results, the most important of which is the reproducibility obtainable in contract with previous confusion on this point. Tests have been conducted on two major modifications of the basic design: a self-shielded diode, and a rugged short body - short electrode version. The results indicate that the modified versions are not applicable in the XR-8 Fuze because of the necessity for design changes in the fuze structure, which is now in an advanced stage of development. The modifications, however, do appear to have excellent properties for other applications, such as timing circuits and high acceleration requirements. The Dynamic Breakdown Voltage Tester has also been used to study the breakdown voltage properties dependent on the rate of voltage application, with the results indicating that breakdown voltage increases with increase in voltage-time gradient of the applied voltage.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 2784 13 April 1953

The work of this report was performed under Bureau of Ordnance Task Assignment NOL-Re2b-11-1-53 in connection with the development of the XR-8 Fuze. The information given herein is intended for use by other Government activities which are concerned with the design of ordnance fuzes using a variety of electrical delay circuits.

The quantitative data listed are to be considered tentative only and may be modified or superseded by future reports. They represent the findings of the author and his associates to date. Conclusions reached in this report should be treated with reserve and accepted only after further experimental verification. Special acknowledgement is given to Mr. Elwood H. Mullins and Mr. Samuel Globe for many informative discussions, and to Messrs. A. A. Burgess, Jr. and R. B. Bowser for their assistance in circuitry, taking data, and computation.

Ref: (a) NAVORD Report 1576, Terminal Development Report on Electric Rocket Fuze XR-8D
(b) NAVORD OS 5909, NAVORD Ordnance Specification: Cold Cathode Diode Tubes XD-1B, XD-2B, and XD-3B
(c) Brownlee, K. A., Industrial Experimentation, Chemical Publishing Company, Inc., Chapter VII
(d) Report EL.1467, Royal Aircraft Establishment (England), An Investigation of the Striking Voltage Characteristics of the CV.91 Cold Cathode Diode, by N. E. G. Hill, September 1949
(e) Report EL.1469, Royal Aircraft Establishment (England), Small and Robust Cold Cathode Tubes for Timing Circuits, by A. H. Mitchell, April 1950
(f) Loeb, L. B., Fundamental Processes of Electrical Discharges in Gases, J. Wiley and Sons, Inc., 1939 (pp. 336-370)
(g) Jacobs, H., Freely, J., and Brand, F. A., The Mechanism of Field Dependent Secondary Emission, Physical Review, Vol. 88, No. 3, November 1, 1952 (pp. 492-499)

EDWARD L. WOODYARD
Captain, USN
Commander

S.W. Booth

S. W. BOOTH
By direction

CONTENTS

ILLUSTRATIONS

AN INVESTIGATION OF SOME PROPERTIES OF COLD CATHODE DIODES

INTRODUCTION

1. The cold cathode diodes which are the subject of this report are similar in size to the more familiar General Electric NE-62 type of neon glow tube. They contain two short tubular electrodes and are filled with an argon-neon mixture. Encircling the glass envelope of the diode is a strip of paper treated with a radium-phosphor mixture (Figure 1). Each phosphor band contains about 0.1 microgram of radium. The natural radioactivity is sufficient to excite the phosphor, which emits primarily in the low visible and ultraviolet range. The electrodes of the diodes are photosensitive; and the net electron emission is used to keep the level of primary ionization relatively high in order to reduce the statistical time lag of breakdown, when sufficient voltage is applied, to a minimum. The three diode types herein considered are the XD-1B, XD-2B, and XD-3B; and the nomenclature represents nominal breakdown voltage values of 100, 150, and 225, respectively.

2. The diodes are designed to meet specifications set up for the XR-8 Electric Rocket Fuze circuit (reference (a)). Briefly, this circuit consists of three parallel branches, each containing one of the three types of diodes, in series with a condenser across which is an impact switch and a primer of specific time delay. In use the pilot would operate a charging button which applies a specified amount of voltage across the circuit of magnitude sufficient to break down only the XD-1B Diode, or both the XD-1B and XD-2B Diodes, or all three diodes. This furnishes a method of selective time delay, since the XD-1B is in series with the longest delay primer, the XD-2B is in series with a primer which has a shorter delay, and the XD-3B is in series with an instantaneous primer. The diodes than act as switches in this application to select the branch of the circuit having the proper delay in accordance with the applied voltage.

3. The diodes have been subjected to a variety of tests to examine their breakdown voltage and energy transfer characteristics under varying conditions. The purpose of the tests can be considered as twofold: to find out if the diodes meet the breakdown voltage and energy transfer characteristics required by the specifications which were set up for the XR-8 Fuze circuit, and to examine the feasibility of relaxing any of the existing specifications to advantage; and to study the factors which affect the properties of cold cathode diodes in general.

Excerpts from Existing Specifications

4. Breakdown voltage specifications are given in Table 1(A). Energy transfer specifications (see reference (b)) require that when a 500 microsecond pulse, with tolerance limits on the pulse duration of +0 and -100 microseconds, of a specified voltage is applied to the diode, sufficient energy should be passed to charge a 0.1 microfarad condenser to 40 volts. The circuit also contains a 750 ohm resistance in series with the diode and the condenser to simulate the fuze circuit. The size of the applied voltage is given in Table 1(B).

5. In place of the latter requirement, and owing to the difficulties inherent in producing a controlled length pulse, NOL has been using a long duration square wave of the specified magnitude applied across a 750 ohm resistor, the diode under test, and the 0.1 microfarad condenser. The time required to charge the condenser to 45 volts is measured. It is felt that more can be learned by this procedure than by a simple test of whether or not the diode meets the energy transfer specification under the controlled length pulse test.

Breakdown Voltage Tests

6. The breakdown voltage tests were begun with the Dring-Mayer Diode Tester, made by the Thomas A. Edison Company. Briefly, for this test the tester can be used in two ways: First, the voltage can be set at a desired value and a step voltage applied to the diode by means of some external switch. If the diode breaks down, the tester detects this by firing a thyratron. Secondly, the voltage can be varied with a motor driven helipot, which increases the voltage at the rate of about 14 volts per second. When the pedal-type switch which actuates the drive is depressed, a potential difference of 70 volts is instantaneously applied to the diode, after which the 14 volt per second build-up of applied voltage is added to the 70 volts. When the diode fires, the thyratron actuates a relay which stops the motor, and the breakdown voltage is indicated on a luminous dial on the test set. The breakdown voltage can be read directly to 0.1 volt, and the tester has an over-all accuracy of ±0.1 percent.

7. Preliminary tests were made on the diodes in daylight, using the voltage gradient of 14 volts per second. For 200 diodes of each type tester, it was found that the following amount fell outside the specified breakdown voltage tolerances:

Type	Number of Diodes Outside Limits	Percent
XD-1B	23	11.5
XD-2B	61	30.5
XD-3B	6	3.0

The data is presented graphically in Figure 4.

8. Since the diodes are intended for use in the dark, however, it was decided to make tests in total darkness. Consequently, the diodes were mounted in polystyrene racks, ten diodes to each rack, and the racks were stored in a large, light-tight metal chest which was kept in the photographic darkroom. To make measurements a rack was removed from the chest and loaded into a small brass test box with light-tight terminal posts mounted on the outside. This operation was performed in total darkness. The box was then removed to the light for the purpose of making measurements.

9. Several tests were performed on 200 XD-2B's thus stored. The voltage was set at 137.9 volts (or 0.1 volt below the lower tolerance limit), and this was applied to the diodes in each polarity using, first, a mercury switch and, then, a mechanical galvanometer key switch. This was done to examine the effects of using different types of switches on breakdown voltage. It should be noted that the diodes are not intentionally polarized but, due to random lack of symmetry in construction, they have somewhat different properties depending on the direction in which the voltage is applied. Data on whether or not the diode fired were recorded. Then the same tests were repeated with the voltage set at 162.1 volts (or 0.1 volt above the upper tolerance limit). An interval of at least 30 minutes was allowed between successive breakdowns. Similar tests were made on 60 each XD-1B's and XD-3B's. Results are given in Table 2. One can test the hypothesis, once having combined the results of both positive and negative polarity at a given voltage setting and for a given type of switch, that there is no difference in the number of rejects obtained between the mercury switch and the galvanometer key. This has been done using the simple Chi-square test of statistics. The result is that there is no significant difference, with one exception, i.e., the difference in the number of rejects can very easily arise by chance alone. The exception is for XD-2B diodes with 162.1 volts applied. The reject rate is significantly higher when the galvanometer key is used, and one can say on the basis of statistics that by chance alone such a significantly higher reject rate can be obtained about 2% of the time. Despite this very small probability (2 chances in 100 of getting such results in a test of this nature by

chance alone) it can be assumed that this does, in fact, occur by chance since one has the evidence that for XD-1B's and XD-3B's (at lower and higher applied voltages than for XD-2B's) the selection of the switch is not a critical factor in reject rate.

10. The breakdown voltage of each diode (200 XD-2B's and 60 each XD-1B's and XD-3B's) was next measured using the Thomas A. Edison Company motor driven tester with the 14 volt per second gradient, and the means and standard deviations were computed. The results are given in Table 3.

11. A test was then set up to examine the breakdown voltage characteristics of the diodes with repeated breakdowns, using the 14 volt per second gradient. Groups of sixty diodes of each type were selected. Half, or thirty, of each type was tested once and then set aside as a control group. The remaining thirty of each type served as the test group. These were broken down twice a day, once in each direction. An interval of at least thirty minutes was allowed between successive breakdowns of the same diode. This process was repeated for ten days. At the end of this time the motor driven helipot was inoperative. About a week was spent in repair and recalibration of the tester. Then the diodes were again tested for ten days, as before. The control group was broken down again on the last day of the accumulated twenty days of testing.

12. To analyze the data obtained with this test, a statistical process known as analysis of variance with a residual was employed (reference (c)). The variance is merely the square of the standard deviation, the latter having a familiar statistical meaning. The variance has the property that if a process has a number of factors each contributing to the total variance of the final product, then this total variance is equal to the sum of the component variances, assuming the factors are acting independently. This property of addition makes possible the technique known as analysis of variance whereby the total variance of a process can be analyzed into its component factors, the relative importance of which can then be assessed.

13. To reduce this into terms of the tests performed on the diodes, assume that for each individual diode there is a variety of external and internal factors which affect the breakdown voltage on successive tests. The internal causes may be thought of as "aging". The external causes may be, for example, temperature, humidity, cosmic rays, etc. No effort is made to control the external causes, and the effects of these two sources of changes in breakdown voltage are lumped together. They cause a dispersion, or variance, of

breakdown voltage of an individual (average) diode measured on successive trials. Besides this source of variance, there is also the fact that in a sample of diodes of the same type, the diodes differ from one another. This gives us an "among classes" variance, considering a collection of breakdown voltage readings on a single diode as a "class". In addition, there is a residual variance which cannot be attributed to the aforementioned causes. It may be regarded as a measure of randomness, or experimental (Gaussian) error. One uses this as a standard for comparison with the other components of variance. Only if the latter are significantly large in comparison with the residual variance (as determined by certain statistical tests such as Fisher's Z-test) are they statistically significant.

14. In the process of this type of statistical analysis the means and standard deviations for individual diodes were computed and also the over-all mean for different diode types. The results are given in Table 4, and the analysis of variance is given in Table 5.

15. The data computed from the control group did not furnish any additional significant information; and, consequently, the control group was of no value.

16. Data taken during August and September of 1950 on 50 preproduction samples of each type were analyzed in the same way as the more recent data. This comparison is summarized in Table 6.

Energy Transfer Tests

17. The apparatus used to perform these tests is the Text Set XR-27A Diode Tube Tester. A square pulse of controlled amplitude sufficient to fire the diode is applied across the diode and simultaneously starts a Potter Electronic Chronograph. The diode is in series with a 0.1 microfarad condenser and a 750 ohm resistor. When the diode fires, the condenser begins to charge. When the voltage across the condenser reaches a predetermined value (in this case 45 volts), a calibrated voltage detecting circuit causes a thyratron relay circuit to become activated. This provides a pulse which stops the chronograph. The time measured is hereafter referred to as the charge time. The delay caused by the circuitry is negligible. The same experimental group of diodes which was used for consecutive breakdown voltage tests was also used for the charge time tests, including the control group, so that sixty diodes of each type were used. As the first phase of the experiment, the nominal overvoltages required by the specifications (Table 1) were used. These voltages are 130, 195, and 295 for the XD-1B's, XD-2B's, and XD-3B's, respectively. The charge time for each breakdown

was measured once a day for ten days, with the voltage being applied in the same polarity each time. The same process was repeated using lower overvoltages, values which are 20% in excess of the nominal breakdown voltage. These lower voltages are 120, 180, and 270 for the XD-1B, XD-2B, and XD-3B, respectively.

18. The data obtained are difficult to analyze rigorously. Of primary interest is the number of failures with regard to the specifications. This is shown in the histograms of Figures 5, 6, and 7; and the reject rate is summarized in Table 7. It is of great interest and practical importance to know how the charge time is affected as a function of the overvoltage. It is, however, difficult to make an analysis of this, since, as has been observed, the breakdown voltage of an individual diode itself appears to have a fairly large dispersion, and the charge times measured for an individual diode have a very large dispersion.

19. The question was later brought up of whether it was advisable, from the standpoint of charge time of diodes, to relax the specifications on the charging voltage to be used. Consequently 100 diodes of each type were subjected to charge time tests with applied voltages covering the range from 20% to 30% overvoltage in increments of approximately 2%. Each diode was broken down twice at each applied voltage, so that 200 readings were made at each voltage. Table 8 shows the voltages applied for each tube type. With the exception of the 120 volt data for XD-1B's, the data at 20% and 30% overvoltage (31.1% for XD-3B's) are taken as that of paragraph 17, plotted in Figures 5, 6, and 7, which were taken from 60 diodes of each type, ten measurements on each. Except for the 120 volt data for XD-1B's, the data from the two different groups of samples correspond with an acceptable degree of homogeneity.

20. For each set of data (i.e., each tube type at each voltage) the percentile points for charge time were taken over a range from the 80th percentile to 99.5%, twelve percentile points in all, at each voltage setting. These data have been plotted on Figures 8, 10 and 12. On each graph (one graph for each tube type) there is plotted the charge time against percent passing for each applied voltage. On Figures 9, 11, and 13 the charge time is plotted against applied voltage for each percentile.

21. Special attention is paid to the 98th percentile point and curve. For XD-1B's, the 98th percentile curve intersects the 120 volt applied voltage line at about 875 microseconds. For XD-2B's, the 98th percentile curve intersects the 180 volt line at about 900 microseconds. For XD-3B's, the corresponding intersection is at about 650 microseconds.

It is thus indicated that, with regard to the operation of the General Electric diodes, the charging voltage limits can be opened up to include an overvoltage as low as 20% of the nominal value; and 98% passing can be achieved if it can be shown that about 1000 microseconds are available for charging the fuze circuits.

Dynamic Tube Drop

22. To study whether the charge time readings obtained are due primarily to the dynamic impedance of the tube being relatively high or whether most of the time is consumed in tube breakdown, a series of breakdown time tests was made. The diodes tested were the same as those used for the charge time tests described in paragraph 17, and each diode was broken down 11 times. The tests were made using Test Set XR-27A, referred to in paragraph 17, with circuit similar to that used for charge time tests. The voltages used were the nominal 30% overvoltages, i.e., 130, 195, and 295 for the XD-1B, XD-2B, and XD-3B, respectively. The data is presented in the histograms of Figures 14, 15, and 16. Figures 17, 18, and 19 show this data plotted in the form of curves of breakdown time versus percentile. If we compare, at the same percentile point in their respective distributions, the charge time and the breakdown time, we can get an idea of the average voltage drop across the diodes during the time the condensers are charging. The voltage available for charging the condenser is equal to the difference in applied voltage minus the tube drop, and the resultant circuit can be considered as having a 750 ohm resistance and 0.1 microfarad condenser, thus a time constant of 75 microseconds. The tube drop can be calculated from the formula

$$45 = (E_A - E_T)\,(1 - \epsilon^{-\Delta t/75})$$

where the condenser charges to 45 volts, E_A = voltage applied to the circuit, E_T = tube drop, and Δt = difference in time between charge time and breakdown time. The calculations are made using the 80th percentile point (Table 9), and the results are:

Tube Type	Average Tube Drop
XD-1B	81 volts
XD-2B	131 volts
XD-3B	220 volts

It should be emphasized that these values are average tube drops during the condenser charging interval from zero to 45 volts only. The tube drop at or just prior to extinguishing is in the order of 70 volts for all three tube types,

determined experimentally by observing the difference between the applied charging voltage and the final condenser voltage after cut-off. The average tube drop is of value in anticipating the times involved in charging a circuit with three branches, each with a condenser in series with a diode.

Dynamic Breakdown Voltage Tester

23. All the measurements of breakdown voltage previously made used either a step voltage or a 14 volt per second voltage gradient on the Thomas A. Edison Tester. In order to study the effect on the breakdown voltage of varying voltage time gradient, the Dynamic Breakdown Voltage Tester Test Set XR-28A, hereafter referred to as DBVT, was designed. With this instrument the voltage gradient applied to test diodes can be selected in the range from approximately 10 volts per second to 100 kilovolts per second, varying the gradient in steps by a factor of 10 per step. The general wave form of the voltage applied to the diode approximates a true exponential curve. To know the voltage gradient exactly, at the time of breakdown, one must make use of either a measured value of breakdown voltage or a measurement of time elapsed until breakdown occurs by means of the following relations:

$$v_B = V_A\,(1-e^{-t/RC})$$

$$\left.\frac{dv}{dt}\right]_{v=v_B} = \frac{1}{RC}\,V_A e^{-t/RC} = \frac{V_A - v_B}{RC}$$

where v_B = breakdown voltage of the diode
V_A = maximum voltage applied
RC = time constant of the circuit
t = time elapsed until breakdown occurs

Provision is made to measure t by means of a Potter Chronograph, but in practice the voltage gradient is taken to be that which prevails for an average breakdown voltage of a given tube type, which can be calculated by inserting the average v_B into the second formula above.

24. Provisions have also been incorporated in the tester to modify the exponential wave form applied to the diode in two ways: First, a predetermined bias of either polarity, not sufficient to break down the diode, can be applied instantaneously and followed immediately by the remaining portion of the exponential curve. Second, this same bias can be applied for a predetermined time before the exponential curve is applied to the diode. The magnitude of this bias is variable.

25. For a brief explanation of the circuitry of the DBVT refer to the block diagram, Figure 3. A 6C4 Triode, operated as a cathode follower, is biased just to cut-off; a voltmeter across the cathode resistor reads zero; and the voltage across the diode is also zero. When the operating switches are closed, a 2D21 Thyratron (Thyratron 1) fires and current begins to flow through a selected resistor (R) and capacitor (C), which determine the time constant. As the grid of the cathode follower becomes more positive (when the capacitor charges), the drop across the cathode resistor follows the voltage on the grid, which in turn appears across the test diode. When the voltage reaches the critical value, the diode fires. The positive pulse resulting is amplified and appears on the grid of Thyratron (2) (a 2D21). This in turn fires, pulling down the plate potential of Thyratron (1), thereby extinguishing the applied charging voltage. The capacitor ceases to charge and holds a constant potential on the grid of the cathode follower. The voltmeter then indicates the breakdown voltage of the diode, which is extinguished by Thyratron (2). The inherent time delay is about 2 1/2 to 3 microseconds, so that when the gradient is about 100 kilovolts per second, an error of about 0.3 volts in the breakdown voltage reading is introduced.

26. It was first desired to make breakdown voltage tests at the minimum voltage gradient of the DBVT for the purpose of comparing results from this tester with those obtained from the Edison Tester. This gradient is 8.6 volts per second, as determined by the design parameters of the test set. It is considered close enough to the 14 volts per second of the Edison Tester to give a basis for comparison. Ten diodes of each type were tested for 10 days each, with the storing and handling for this test being similar to that for the previous tests. The data was subjected to analysis of variance as before; and it was found that the variance for an individual diode becomes almost negligible, whereas it was of considerable importance for Edison Tester results. This raised a question of the validity of results obtained using the Edison Tester. This data is summarized and compared with the Edison Tester results in Table 10.

27. Some of the figures presented in Table 10 have been tested for significant differences by a variance ratio test.

a. The variance ratio comparing the successive breakdown variance for XD-1B Diodes with the Edison Tester for either tests A (first 10 days) or B (second 10 days) with that for the DBVT indicates that the former is significantly greater.

b. The variance ratio comparing the residual variance for XD-1B's with the Edison Tester with that for the DBVT

indicates that the former is significantly greater. In fact, if one adds the successive breakdown variance to the residual variance and considers the sum as the variance of an individual diode, it is seen that one gets a standard deviation of about 4 1/2 volts using the Edison Tester, as compared with about 1 volt for the DBVT.

c. The variance ratio comparing the successive breakdown variance for XD-2B Diodes with the Edison Tester for test B (second 10 days) with that for the DBVT indicates that the former is significantly greater. This is not true for test A (second 10 days). (The 5% probability level is taken as the criterion of significance.)

d. The relatively high value of the between diodes variance for the XD-2B and XD-3B tests made with the DBVT as compared with those for the Edison Tester results is not significant statistically. It should be noted that this is derived from only ten diodes, drawn from the original 30 tested with the Edison Tester, and thus the possibility of this relatively high variance occurring randomly is indicated.

e. The relatively high value of the successive breakdown voltage variance for XD-3B's for tests made with the DBVT has no physical meaning, since the breakdown voltage is only read to the nearest volt. In fact, in each case for XD-3B's this variance should be combined with the residual and the sum considered as the variance for an (average) individual diode.

28. The ten diodes of each type tested with the DBVT for this test were drawn from the thirty which had been subjected to the test of breakdown voltage on the Edison Tester. The results on the thirty diodes tested in both testers are compared in Table 11. In the same table the mean breakdown voltages for individual diodes on the different testers are compared to see if they are significantly different. It is seen that for one XD-1B, four XD-2B's, and seven XD-3B's there are significant differences between the means at the 5% level of significance. (If differences between means as large as those observed can be obtained by chance alone at least 5% of the time, then the difference is not considered significant. This is a commonly used criterion in the application of statistics to engineering problems.) In almost all these cases, however, the actual magnitude of the difference between the mean breakdown voltages is very small and is not considered to be of practical importance.

29. The mean breakdown voltage for each tube type of all the diodes measured on both the Edison Tester and the DBVT was computed and is summarized in Table 11A. It is seen

that for XD-1B's and XD-2B's the mean obtained from DBVT results approximates the desired nominal breakdown voltage better than the mean obtained for Edison Tester results. This is not true of the XD-3B's, where the mean breakdown voltages are essentially the same in all the tests. The reason for the small decrease in breakdown voltage (on the XD-1B's) measured on the DBVT may be the use of a smaller voltage gradient, as will be later discussed. In the Edison Tester the voltage gradient is 14 volts per second. In the DBVT the circuit parameters are so adjusted as to give voltage gradients of 8.6 volts per second for XD-1B's, 9.6 volts per second for XD-2B's, and 9.5 volts per second for XD-3B's as average values computed for breakdown voltages of 100, 150, and 230, respectively.

30. It was felt that the large variance of breakdown voltage of individual diodes found with the Edison Tester and not found with the DBVT might be due to the 70 volt step which appears across the diode instantaneously when the Edison Tester is used. To investigate this the DBVT was arranged such that a 70 volt step could be applied initially, as in the Edison Tester, and then the voltage across the diode built up at the same rate as in paragraph 29. The same group of diodes previously tested on both the Edison and DBVT (ten diodes of each type) was broken down ten times each.

31. The results are interesting for two reasons: First, in an analysis of variance carried out as in the previous tests (Table 12), it appears that the 70 volt step may indeed be responsible for the large variance for breakdown voltage of an individual diode previously observed for XD-1B's. For this tube type, σ_1^2, the "within class" variance, or variance for an individual (average) diode, for the test on the DBVT using the 70 volt step is significantly larger than σ_1^2 without the 70 volt step, but not significantly different from that obtained in Edison Tester results (in the ten measurements made after the helipot of the Edison Tester had been replaced). This is also true for σ_0^2, the residual variance, though not so distinctly. For XD-2B's both σ_1^2 and σ_0^2 for the DBVT results with the 70 volt step are smaller than for any of the previous tests. The explanation for this is not apparent, but it may well be that for XD-2B's, unlike the XD-1B's, the application of the 70 volt step is of no consequence. This is indicated by the fact that this value of σ_1^2 is not <u>significantly</u> smaller than the other observed values of σ_1^2, and that σ_0^2, though significantly smaller than for the Edison Tester results, is not significantly smaller than for the DBVT results without the 70 volt step. This leads to the belief that, perhaps, in addition to a very important refinement the elimination of the 70 volt step makes in test results, there is an additional refinement,

much less important, which might be due to the improvement in the method of voltage application. That is, for the Edison Tester the voltage application is controlled by a physically moving contact on a helipot, while for the DBVT the voltage application is controlled by build-up of electronic charge on a condenser. A retest on the Edison Tester was run several times to check whether any tube stabilization had occurred over the test period. It was found that the variances for individual diodes were large, as before, so that stabilization is not a cause of the smaller variances for individual diodes observed with the DBVT.

32. The second interesting result obtained for the DBVT tests with the 70 volt step was observed for XD-3B's. From the 10 readings of breakdown voltage obtained for several of the diodes, there appeared to be two preferred values of breakdown voltage, differing by as much as 20 volts, about which the breakdown voltage clustered. That is, a bi-modal type of distribution of breakdown voltage was observed. Now, referring to the two modes as the higher mode (corresponding to the larger breakdown voltage) and the lower mode (corresponding to the lower breakdown voltage), the following facts were noted:

a. Five out of the ten XD-3B's thus tested exhibited a bi-modalism for the breakdown voltage.

b. The higher mode can be considered as the "normal" mode of breakdown, i.e., the higher mode is the one which corresponds to breakdown voltage results noted in previous tests.

c. On any given day of test, all the diodes exhibiting this bi-modal effect break down with the higher mode of breakdown voltage or all with the lower mode of breakdown voltage, but not some with the higher and some with the lower.

d. The lower or "abnormal" mode of breakdown voltage is a true breakdown of the diode. That is, it was felt possible that the DBVT could record a breakdown if a very high leakage current were being passed by the diode. This was not verified by checking, however. On the contrary, when Test Set XR-27A was used in the leakage current test, the "abnormal" mode of breakdown could be observed as a true breakdown. Furthermore, on a day when the "abnormal" mode of breakdown could be observed with the DBVT, it could be observed with the leakage current test of the Test Set XR-27A. On days when the "normal" mode was observed with the DBVT, only the "normal" mode was observed using the XR-27A.

No good explanation of this bi-modal effect has been verified to date. Recently, research being conducted at the

General Electric Lamp Development Laboratory has indicated that the condition of the electron emitting coating on the electrodes of the diode is a critical factor in determining breakdown voltage, and there is a further indication that the condition is inherently unstable. This may, in time, furnish an explanation of the bi-modal effect as well as other heretofore unexplained effects.

33. The mean breakdown voltages for individual XD-1B Diodes as measured with the 70 volt step initially applied on the DBVT are compared with those obtained without any voltage step in Table 13. It can be seen that for all nine diodes the mean breakdown voltage is significantly smaller when measured with the 70 volt step.

34. It can easily be shown that when the voltage step initially applied to the diode is not sufficient in itself to break down the diode, the voltage gradient at the instant of tube breakdown is independent of the magnitude of the initial voltage step. Consider a simple circuit consisting of a battery with voltage E_b, a resistance R, and a condenser C (across which the diode is placed), with a series switch. Initially the switch is open and a voltage E_o is across the condenser. The general formula for the voltage across the diode (condenser) as a function of time after the switch is closed is:

$$e_c = E_o e^{-t/RC} + E_b(1 - e^{-t/RC}) \qquad (1)$$

where e_c = the instantaneous voltage across the condenser at time t

$$e_c = E_b + (E_o - E_b)e^{-t/RC} \qquad (1a)$$

Solving for $e^{-t/RC}$:

$$e^{-t/RC} = \frac{E_b - e_c}{E_b - E_o} \qquad (2)$$

Now, if e_B = breakdown voltage of diode, when e_c reaches e_B we get

$$e^{-t/RC}\Big]_{e_c = e_B} = \frac{E_b - e_B}{E_b - E_c} \qquad (3)$$

The voltage gradient can be found by differentiating equation (1a) with respect to time:

$$\frac{de_c}{dt} = \frac{E_b - E_o}{RC} e^{-t/RC} \qquad (4)$$

and when $e_C = e_B$, substituting the result of equation (3):

$$\left.\frac{de_C}{dt}\right]_{e_C=e_B} = \left.\frac{E_b - E_o}{RC} e^{-t/RC}\right]_{e_C=e_B} = \qquad (5)$$

$$\frac{E_b - E_o}{RC}\left(\frac{E_b - e_B}{E_b - E_o}\right) = \frac{E_b - e_B}{RC}$$

The result is independent of E_o, the magnitude of the initial step.

35. Thus it is seen that the gradient at the instant of breakdown depends on e_B, the breakdown voltage alone, and the fixed parameters E_b, R, and C, and not on E_o. It follows that the gradient is the same whether the 70 volt step is applied initially or not, and thus difference in mean breakdown voltage for the two tests performed with the DBVT is not due to any change in gradient.

36. Experiments conducted at the General Electric Lamp Development Laboratory in Cleveland, Ohio have uncovered instances of diodes breaking down at an abnormally low voltage when a sudden voltage step is applied. The reason for this has not yet been satisfactorily explained, but it appears that this is a manifestation of the same phenomenon which causes the diodes to break down at a lower voltage when a 70 volt step is initially applied. It may be that the application of an instantaneous voltage suddenly accelerates a large number of electrons either in space (the primary ionization) or from the emitting surface of the cathode and causes a high degree of ionization by cascade multiplication, giving rise to reduced breakdown voltage. At any rate, the evidence seems to lead to the conclusion that the Edison Tester, using a 70 volt step, gives erratic results.

37. In the Edison Tester, although there is an initial voltage step of 70 volts, there is the additional factor of a voltage gradient slightly higher than that which is encountered with the DBVT. It is a combination of these factors (the voltage step which decreases the breakdown voltage and the increased gradient which increases it) that may give rise to a slightly higher breakdown voltage on measurements made with the Edison Tester.

38. In early tests on breakdown voltage made on the Edison Tester, when individual diodes were exhibiting large variances in tests of repeated breakdowns, it was felt that the interval of waiting between successive breakdowns was a critical factor in determining the breakdown voltage. It was not possible to verify this, however, because the individual readings for a given diode had such a large scatter. With the DBVT consistent measurements could be made on individual diodes, with very little scatter. In fact, as the

data of Table 11 shows for the XD-1B's, there is almost no scatter introduced by instrumentation or experimental method. Therefore a test was set up using the DBVT and measuring breakdown voltage on successive tests, with time intervals between successive breakdowns varying from several minutes to several hours, and comparing the resulting scatter with that obtained when the intervals between successive breakdowns were of the order of days. The results show that when using the DBVT with no voltage step applied, successive measurements taken with intervals of two hours have the very small scatter which is found using intervals of several days. If intervals of between 15 minutes and 2 hours are used, measurements exhibit increased random scatter. If measurements are made with intervals of much less than 15 minutes, e.g., 5 minutes or 10 minutes, the successive breakdown voltages measured tend to diminish and reach a sort of stabilization and, consequently, have very little scatter, although giving too low a value for breakdown voltage.

Shielded Diodes

39. The General Electric Company furnished NOL with samples of XD-1B Diodes, which are coated with a conducting shield which almost completely covers the entire glass body of the diode and physically touches one of the electrodes. One group of 10 diodes (Group 1) was originally manufactured in the fall of 1950 and was rejected on breakdown voltage tests at the factory because the breakdown voltage was too high. The shielding process was added at a later date for the experimental tests. A second group of 9 diodes (Group 2) was manufactured in the fall of 1951 using a different exhaust machine to evacuate the diode envelopes and was also rejected because of too high a breakdown voltage. Another group of 10 diodes (Group 3) was manufactured in the Spring of 1952 using a new exhaust machine. Each of these 29 diodes was broken down ten times each, using the Edison Tester, first with the shield positive and then with the shield negative (ten measurements each way). The results, i.e., the mean breakdown voltage and the standard deviation for each individual diode, are given in Table 14. There are two outstanding results obvious from the data:

a. The standard deviations for successive breakdown voltages is very small in every case except one (Group 1, Diode 2, shield negative), being almost negligible in comparison with those obtained for unshielded diodes when tested on the Edison Tester.

b. The breakdown voltage readings with the shield negative are above the specification limits (92-108 volts), and

with the shield positive the readings are mostly within specification limits but are all very low. The General Electric Company is unable to manufacture XD-1B Diodes which have a breakdown voltage low enough to be within specifications when the shield is negative. On the other hand, NOL cannot use diodes with positive shields in the XR-8 Fuze because of the problem of insulating the shield from the fuze body, which is normally at ground potential. At present, space limitations prohibit including the shield because the diode diameter is too large to allow space for it and the required insulation.

Short-Short Diodes

40. The General Electric Company also furnished NOL with fifty experimental diodes comparable to the XD-1B type but with shorter body lengths and shorter electrodes than the XD-1B Diodes heretofore developed for use in the XR-8 Fuze. These diodes are herein referred to as short-shorts. The primary physical difference between the short-shorts and the conventional length diodes is that the short-shorts have, in addition to shorter electrodes, a 3/16" radium-excited phosphor band (the widest size which can be used on the short body), whereas the conventional diodes have a 1/4" radium-excited band of the same relative efficiency. Tests of energy transfer and breakdown voltage have been conducted on the short-shorts.

41. For the energy transfer tests 40 short-short diodes were broken down 5 times each at 120 volts and 130 volts so that 200 readings were available at each applied voltage. The equipment used was the Test Set XR-27A, and the time required to charge a 0.1 microfarad condenser in series with a diode and a 750 ohm resistor to 45 volts was measured by means of a Potter Chronograph. The data thus obtained is given graphically in Figures 20 and 21 in the form of charge time versus percent passing and compared with the data obtained for the conventional diodes, plotted on the same figures.

42. The following two cases are considered separately as rejects:

a. When the voltage applied is 130 volts, the measurement is considered a reject unless the condenser charges to 45 volts within 500 microseconds. This corresponds approximately to conditions established by existing specifications (reference (b)).

b. When the voltage applied is 120 volts, the reading is considered a reject unless the condenser charges to 45

volts within 1000 microseconds. This corresponds roughly to the lower limit referred to in paragraph 20.

43. The graphs show the following reject rate (approximately):

	Reject Rate Case (a)*	Reject Rate Case (b)**
Conventional Length	1.5%	1%
Short-Shorts	16.5%	6%

* 130 volts applied, 500 microsecond limit
** 120 volts applied, 1000 microsecond limit

44. Ten each of the short-shorts and conventional diodes were set aside and altered by removing part of the phosphor bands on each. Originally the phosphor band on the short-shorts was 3/16" wide, while that on the conventional tubes was 1/4" wide. The bands on both types were cut down to 1/8". If a half-life of 20 years is assumed for the radium which activates the phosphor, from the viewpoint of radioactivity alone the reduced band width represents a shelf time of 20 years for the conventional diodes and about 11.8 years for the short-shorts.

45. The ten diodes of each kind were broken down 5 times each, and the data is plotted in Figure 22 on the basis of 50 readings for each curve. An interesting feature of this graph is that the two curves are fairly close to one another, indicating that the band width is the factor which influences charge time most, rather than the electrode length. The amount of data available is actually too small to make the results conclusive. The reject rate under the existing specifications is too high to be shown on Figure 22, but under the lower limit of paragraph 20 (1 millisecond charging pulse at 120 volts) the reject rate is about 4 1/2 percent for the conventional diodes and about 6 1/2 percent for the short-shorts, which is not considered prohibitive.

46. The breakdown voltage of the short-short diodes was measured on the DBVT using approximately a 10 volt per second gradient. For the 40 short-shorts tested, the mean breakdown voltage is 102.8 volts and the standard deviation is about 2.7 volts. Thus, about 97% of such short-shorts would be expected to fall within the breakdown voltage specification limits on XD-1B's, between 92 and 108 volts. The distribution for the 10 short-shorts with the band reduced to 1/8" is essentially the same.

47. From these results it is seen that the short-short diodes are acceptable with regard to breakdown voltage

specifications but fail existing charge time specifications and also fail the 1 millisecond, 20% overvoltage limit. Also, given groups of short-shorts and conventional diodes have a lower reject rate with a 1 millisecond, 20% overvoltage charging pulse than under existing specifications.

Effect of Voltage-Time Gradient on Breakdown Voltage

48. The DBVT was used to measure the effect on the breakdown voltage of varying the voltage-time gradient for the applied voltage. Tests were made on twenty diodes of each type (conventional length). The circuit parameters of the DBVT were so adjusted as to provide the following gradients at the indicated values of breakdown voltage. (As has been pointed out, the gradient depends on the breakdown voltage and can be computed from the following relationship:

$$\left.\frac{dV}{dt}\right]_{V=V_B} = \frac{V_A - V_B}{RC}$$

where V_B = approximate breakdown voltage, V_A = asymptotic value of applied voltage, and RC = circuit time constant.)

Tube Type	V_B	$V_A - V_B$	Gradient
XD-1B	100 volts	86 volts	8.6 V/sec ⟶ 8.6×10^4 V/sec
XD-2B	150 volts	96 volts	9.6 V/sec ⟶ 9.6×10^4 V/sec
XD-3B	230 volts	95 volts	9.5 V/sec ⟶ 9.5×10^4 V/sec

Each of the twenty diodes was tested at five different voltage gradients, each test (at a given gradient) consisting of five measurements of breakdown voltage.

49. It was noted that the high degree of reproducibility which was previously obtained using the smallest voltage gradients is not obtained when using the higher voltage gradients; however, enough reproducibility is obtained so that comparison of breakdown voltage as a function of voltage can be made in most cases. This is done by taking the mean breakdown voltage at a given gradient and comparing it with the mean breakdown voltage at the gradient which differs by a factor of 10, using Student's t-test. This test considers the relative importance of difference in means with respect to the variance in the measurements used to compute each of the means and tells the probability of obtaining such a difference in means by chance alone.

50. The results obtained are summarized in Tables 15, 16 and 17. The mean values of breakdown voltage for different

voltage gradients are tabulated in these tables. The results of applying the t-test are also shown, when the mean breakdown voltage of an individual diode at a given gradient is compared with mean breakdown voltage of the same diode when tested with the gradients which differ by a factor of 10 (higher and lower). The 10% probability level is used as the level of significance, i.e., the means are considered different only if there is less than a 10% chance of obtaining such a difference by chance alone.

51. The tables show that there is (in general) an increase in breakdown voltage with an increase in voltage gradient. There is apparently no simple relationship between the breakdown voltage and the voltage gradient. Individual diodes behave differently from one another in this respect. A report of the Royal Aircraft Establishment (reference (d)) discusses the problem of breakdown voltage as a function of gradient. Investigations at the Royal Aircraft Establishment carried out on the British CV.91 cold cathode diode resulted in a relation of this form:

$$V_B - V_D = B \left(\frac{dV}{dt}\right)^{1/2}_{V=V_B}$$

where V_B = breakdown voltage measured

V_D = a constant which is a property of the individual diode. It is not the static measured breakdown voltage but is a value obtained by extrapolation of a curve of the data.

B = a general constant which applies fairly closely to all the CV.91 diodes measured

$\left(\frac{dV}{dt}\right)_{V=V_B}$ = voltage gradient at the instant of breakdown

The report states that the reason higher breakdown voltages are obtained with larger gradients is that the formation time of the discharge causes the applied voltage to reach a higher value at faster rates of rise before breakdown is observed. This statement bears some examination. If this is true, it is implied that the formation time of the discharge, or the breakdown time, is fairly long. Physically, this time is the time lag from the instant at which the voltage is high enough to give rise to secondary emission processes at a high enough level so that the discharge is self-sustaining, until the instant when the electron current reaches a high enough value to be recorded as a breakdown. Now, if a difference in voltage gradient gives rise to a measurable difference in breakdown voltage, then the breakdown time must be rather

long. A relationship of the following type would be indicated:

$$\tau\left[\left(\frac{dV}{dt}\right)_1 - \left(\frac{dV}{dt}\right)_2\right] = V_{B1} - V_{B2}$$

where τ = breakdown time, or formation time

V_B = breakdown voltage

$\left(\frac{dV}{dt}\right)$ = voltage gradient

and subscripts 1 and 2 denote different operating points (corresponding to different gradients)

52. From this relation it can be seen that if τ is of the order of 100 microseconds, and $\left[\left(\frac{dV}{dt}\right)_1 - \left(\frac{dV}{dt}\right)_2\right]$ is about 10^3 volts per second, such as (10^3 volts/sec - 10 volts/sec), then ($V_{B1} - V_{B2}$) is about 0.1 volt, which could hardly be detected with the measuring scheme used. Only if the breakdown time were longer could the voltage difference be detected, or when $\left[\left(\frac{dV}{dt}\right)_1 - \left(\frac{dV}{dt}\right)_2\right]$ is larger than 10^3 volts per second, say, 10^4 volts per second and upward. The British work was done using gradients as high as 10^8 volts per second. Also the CV.91 diode does not use a radium excited phosphor band as a source of energy for primary ionization. Instead, one microgram of radium bromide is introduced into the gas mixture of the diode and the natural radioactivity is converted to primary ionization, probably by collision processes. It is probable, based on test results obtained in the United States, that the level of primary ionization is lower in the CV.91 diodes than in the General Electric cold cathode diodes. We might assume then that the breakdown time will be longer in the CV.91 so that the above relation between breakdown time, gradient, and breakdown voltage might hold.

53. If one tries to apply this type of formula, however, to the experimental work herein described, there is a failure on the following points:

a. The breakdown time (τ) of the diodes is of the order of 5×10^{-5} seconds.

b. The voltage gradients used to take the measurements range from about 10 volts per second to about 10^5 volts per second, and there is a significant increase in breakdown

voltage of the order of 2 volts with a change in gradient from, say, 10 volts per second to 10^3 volts per second.

These points are not compatible with the relation

$$V_{B1} - V_{B2} = \tau\left[\left(\frac{dV}{dt}\right)_1 - \left(\frac{dV}{dt}\right)_2\right]$$

$$= 5 \times 10^{-5}\left[10^3 - 10\right] \simeq .05 \text{ volts}$$

Thus there must be some more basic reason why one obtains a measurable increase in breakdown voltage with increase in gradient. Actually the British used gradients as high as 10^8 volts per second and found that, at gradients of 10^5 volts per second (the upper limit used in this work) or below, the empirical relation reported does not hold too well.

54. As stated above, there must be some fundamental reason why we get an increase in breakdown voltage for increases in voltage gradients which are relatively small. One interesting possibility is the condition of the cathode surface. The electrodes are covered with a thin boundary layer of a substance which, though it has a low work function, may be a dielectric. The most important mechanism which promulgates the avalanche of current in the Townsend region is probably the secondary emission, which is caused by bombardment of the cathode with positive ions caused in the gas by collision (reference (f)). Some recent literature (reference (g)) indicates that when the positive ions strike the front surface of the dielectric, a positive charge is built up there on the front surface, which increases because the ions knock out secondary electrons which are emitted and give rise to other ions on the surface. This builds up a field across the dielectric layer. Now, as more ions bombard the cathode, they may penetrate the outer surface because of the porosity of the dielectric layer and give rise to secondary electrons by a collision transfer process. These secondary electrons are accelerated under the influence of the additional field in the dielectric toward the front surface of the electrode and acquire enough momentum to cause further emission by collision. There is then a type of cascade process in the dielectric film which is similar in nature to the Townsend avalanche which occurs in the gas itself.

55. It may be possible to consider the effect of varying voltage gradient in the following way: When a small voltage-time gradient is used, we may have the additional help of a field set up in the dielectric layer on the cathode and have the breakdown voltage reduced because of the help which the current gets from secondary ionization processes in the dielectric film. When the gradient gets much higher, however,

the voltage across the diode reaches the normal breakdown voltage value before many positive ions reach the cathode. That is, the time required for the applied voltage to reach the (normal) breakdown voltage of the diode is less than that required for all but the closest positive ions to reach the cathode, so there is no field in the dielectric layer to aid in lowering breakdown voltage.

56. It must be emphasized that the remarks in paragraphs 54 and 55 are to be considered as conjecture only, with no real experimental verification. The transit time of a positive ion is computed very roughly in Appendix I and is of the order of 10^{-7} seconds for the conditions chosen. This is not considered too far out of line to fit in with a theory such as is set forth in paragraphs 54 and 55.

CONCLUSIONS

57. The following conclusions may be reached as a result of the foregoing studies:

a. The General Electric diodes manufactured in pilot lot quantity and furnished to the Naval Ordnance Plant, Macon, Georgia for use in the XR-8 Fuze will, in general, meet the existing diode specifications for breakdown voltage. Although there was considerable doubt on this point when tests were being conducted on the Edison Tester, tests made on the DBVT have substantiated the findings at the General Electric Company Lamp Development Laboratory in Cleveland, Ohio and at the Naval Ordnance Plant, Macon, Georgia. This is illustrated most clearly in Table 11. An important corollary of this conclusion is that the Edison Tester is no longer considered reliable for testing XD-1B Diodes.

b. The diodes meet the existing specifications on energy transfer, or charge time, as indicated in Table 8, when a nominal 30% overvoltage is applied, with a very small reject rate. When the applied overvoltage is dropped to a nominal value of 20%, the reject rate rises to between 5% and 10%, taking the specification limit of 500 microseconds. If, however, the time available is taken as 1000 microseconds (which it is felt may be adopted), at 20% overvoltage there is a negligibly small reject rate.

c. The breakdown time of the diodes is satisfactorily short, on the average approximately 50 microseconds. The dynamic tube drop over the range of time required for charging the condenser in the XR-8 Fuze is unexpectedly high, being much closer to the breakdown voltage of the diodes than the maintaining voltage, but it is not high enough to render the fuze circuit inoperative.

d. The Dynamic Breakdown Voltage Tester has proved itself in actual use to be far superior to the Edison Tester with regard to reproducibility of measurements. Using this tester, it has been determined that a time interval of the order of two hours between successive breakdowns is sufficient to allow reproducible measurements.

e. Self-shielded diodes have excellent reproducibility or breakdown voltage measurements, even on the Edison Tester, making them a very superior modification for application in precision timing circuits. Insulation problems in the fuze assembly, however, prevent their use in the XR-8 Fuze. In fact, such a high order of precision is not required in this application.

f. The short-body, short-electrode versions of the General Electric diode, which are desirable for high acceleration applications, meet the existing specifications for breakdown voltage but fail the energy transfer specifications, probably because the body length is too short to carry a full 1/4 inch radium-phosphor band.

g. The breakdown voltage increases over a fairly large range when the rate of voltage application increases. This, however, is not to be confused with applying a step potential at some voltage just sufficient to break down the diode, as is the case in acceptance testing (reference (b)). In the latter case the potential is maintained at this fixed voltage for an interval which is very long compared to the formation time lag of discharge; and the breakdown, in general, occurs at this relatively low value. Thus, in spite of the very sharp rise (rate of voltage application is very large) of the step potential, there is no contradiction of the stated result that breakdown voltage increases with rate of voltage application. This is because the conditions in the two cases are different physically. Though the results in Table 2 indicate that the diodes do not pass in acceptance testing, results from more exhaustive tests of the General Electric Company show that, in general, the diodes do pass. Further tests appear to be necessary, particularly to correlate results from testing with a step potential with results obtained from the DBVT.

APPENDIX

60. APPROXIMATE ORDER OF MAGNITUDE FOR THE TRANSIT TIME OF AN ION.

$F = ma$ — F = force on the ion.
$F = qE$ — m = mass of the ion.
$qE = ma$ — a = acceleration
$a = \frac{qE}{m}$ — q = charge on the ion.
E = electric field.

Assume there is a constant field, then acceleration is a constant.

$X = \frac{1}{2}at^2$ — X = distance which ion moves.
t = time required to move the distance X.

$$t^2 = \frac{2X}{a} = \frac{2X}{qE/m} = \frac{2mX}{qE}$$

Assume we have the constant field caused by parallel plates at a distance d apart.
Then $E = V/d$

$$\therefore \; t^2 = \frac{2mXd}{eV}$$

Let m = 10 nucleon masses
$\simeq 10 \times 2 \times 10^3 \times 9 \times 10^{-31}$ Kgm
$\simeq 1.8 \times 10^{-26}$ Kgm

Let $X = 1mm = 10^{-3}$ meters
$d = 3 \times 10^{-3}$ meters
e = electron charge $= 1.6 \times 10^{-19}$ coulomb
$V = 50$ volts

$$\therefore \; t^2 = \frac{2 \times 1.8 \times 10^{-26} \times 10^{-3} \times 3 \times 10^{-3}}{1.6 \times 10^{-19} \times 5 \times 10} \simeq 10^{-14}$$

$t = 10^{-7}$ Seconds

SUMMARY OF SPECIFICATIONS *
FOR COLD CATHODE DIODES

A- BREAKDOWN VOLTAGE

TUBE TYPE	NOMINAL B. D. V.	PERCENTAGE TOLERANCE	LOWER TOLERANCE LIMIT	UPPER TOLERANCE LIMIT
XD-1B	100 VOLTS	± 8%	92 VOLTS	108 VOLTS
XD-2B	150 VOLTS	± 8%	138 VOLTS	162 VOLTS
XD-3B	225 VOLTS	± 8%	207 VOLTS	243 VOLTS

B - ENERGY TRANSFER

TUBE TYPE	AMPLITUDE OF VOLTAGE PULSE APPLIED	PERCENTAGE TOLERANCE	LOWER TOLERANCE LIMIT	UPPER TOLERANCE LIMIT
XD-1B	130 VOLTS	± 2%	127.4 VOLTS	132.6 VOLTS
XD-2B	195 VOLTS	± 2%	191.2 VOLTS	198.8 VOLTS
XD-3B	295 VOLTS	± 2%	289.1 VOLTS	300.9 VOLTS

* REF A

TABLE 1

BREAKDOWN VOLTAGE TESTS TO COMPARE EFFECTS OF DIFFERENT SWITCHES
SQUARE WAVE PULSE APPLIED

TUBE TYPE	NUMBER TESTED	APPLIED VOLTAGE	SWITCH TYPE	POLARITY	NUMBER OF REJECTS	% REJECTS OF TOTAL NUMBER TESTED	NUMBER OF REJECTS NEGLECTING POLARITY
XD-1B	60	91.9 VOLTS	MERCURY	+	11	18.3%	20
				−	9	15.0	
			GALVANOMETER KEY	+	8	13.3	28
				−	20	33.3	
		108.1 VOLTS	MERCURY	+	5	8.3	13
				−	8	13.3	
			GALVANOMETER KEY	+	7	11.7	11
				−	4	6.7	
XD-2B	200	137.9 VOLTS	MERCURY	+	5	2.5	10
				−	5	2.5	
			GALVANOMETER KEY	+	5	2.5	9
				−	4	2.0	
		162.1 VOLTS	MERCURY	+	18	9.0	35
				−	17	8.5	
			GALVANOMETER KEY	+	21	10.5	55
				−	34	17.0	
XD-3B	60	206.9 VOLTS	MERCURY	+	1	1.7	1
				−	0	0	
			GALVANOMETER KEY	+	1	1.7	1
				−	0	0	
		243.1	MERCURY	+	2	3.3	5
				−	3	5.0	
			GALVANOMETER KEY	+	2	3.3	4
				−	2	3.3	

PRELIMINARY BREAKDOWN VOLTAGE TEST
EDISON TESTER

TUBE TYPE	NUMBER TESTED	APPLIED POLARITY	MEAN BREAKDOWN VOLTAGE	STANDARD DEVIATION
XD-1B	60	+	104.01 ± 0.94 VOLTS	7.29 VOLTS
		−	102.98 ± 0.98 VOLTS	7.58 VOLTS
		+	100.57 ± 0.78 VOLTS	6.06 VOLTS
		−	101.02 ± 0.86 VOLTS	6.62 VOLTS
XD-2B	200	+	155.67 ± 0.58 VOLTS	8.24 VOLTS
		−	154.98 ± 0.60 VOLTS	7.90 VOLTS
		+	154.68 ± 0.60 VOLTS	8.51 VOLTS
		−	153.94 ± 0.53 VOLTS	7.44 VOLTS
XD-3B	60	+	231.55 ± 0.92 VOLTS	7.09 VOLTS
		−	232.06 + 80 VOLTS	6.16 VOLTS
		+	231.64 ± 0.90 VOLTS	6.98 VOLTS
		−	231.61 ± 0.85 VOLTS	6.55 VOLTS

TABLE 3

SUMMARY OF CONSECUTIVE B.D.V. TESTS FOR INDIVIDUAL XD-1B DIODES
All Tests with Diodes in Total Darkness

Rack No.	Diode No.	Ave. for First 10 Firings: Mean B.D.V	Ave. for First 10 Firings: Std Deviation (Sigma)	Ave. for Second 10 Firings: Mean B.D.V.	Ave. for Second 10 Firings: Std Deviation (Sigma)
1	1	109.7	3.10	110.27	4.73
1	2	103.9	4.14	105.47	4.62
1	3	108.6	3.62	108.32	4.43
1	4	105.7	6.89	102.02	3.30
1	5	104.7	3.99	111.16	2.00
1	6	104.2	1.88	100.57	5.17
1	7	95.9	5.91	98.94	3.81
1	8	111.7	6.01	107.37	6.14
1	9	106.7	6.54	107.53	2.75
1	10	97.6	3.80	88.96	3.05
5	1	95.4	3.39	93.11	3.42
5	2	96.3	1.87	96.71	3.52
5	3	99.2	1.88	99.71	3.09
5	4	101.3	1.38	104.53	4.86
5	5	101.5	5.31	105.79	8.76
5	6	98.2	4.09	100.26	4.61
5	7	98.3	4.96	95.23	3.00
5	8	104.0	6.24	100.44	2.80
5	9	110.7	6.50	109.07	6.89
5	10	111.2	4.36	109.91	2.12
7	1	97.5	3.24	100.89	5.10
7	2	103.9	3.91	104.16	7.20
7	3	93.6	2.91	96.87	6.11
7	4	99.4	4.73	102.28	4.23
7	5	115.2	8.04	117.07	5.08
7	6	101.4	3.46	101.08	5.65
7	7	109.4	6.22	110.36	4.80
7	8	104.9	4.99	106.06	5.28
7	9	105.3	6.87	102.98	4.73
OVER ALL AVE.		103.29		103.52	

TABLE 4

SUMMARY OF CONSECUTIVE B.D.V. TESTS FOR INDIVIDUAL XD-2B DIODES

All Tests with Diodes in Total Darkness

Rack No.	Diode No.	Ave. for First 10 Firings Mean B.D.V.	Ave. for First 10 Firings Std. Deviation Sigma	Ave for Second 10 Firings Mean BDV	Ave for Second 10 Firings Std. Deviation (Sigma)
2	1	149.9	0.55	150.78	1.15
2	2	142.9	0.71	143.46	1.33
2	3	152.8	2.31	162.80	3.72
2	4	154.4	1.04	155.32	1.77
2	5	159.7	4.35	160.78	4.73
2	6	153.2	2.81	153.71	2.01
2	7	152.2	2.32	161.37	0.67
2	8	154.3	1.84	153.36	0.97
2	9	156.2	0.57	157.18	0.92
2	10	151.2	0.54	152.56	1.00
9	1	149.7	3.00	149.89	2.08
9	2	152.9	2.11	152.52	0.61
9	3	151.6	2.60	152.97	2.30
9	4	159.9	3.31	159.61	0.85
9	5	158.8	4.79	156.94	0.55
9	6	152.6	3.39	153.89	2.55
9	7	159.2	2.92	159.50	2.00
9	8	151.7	1.01	153.10	3.48
9	9	155.8	2.56	156.58	3.60
9	10	152.2	4.47	153.43	6.26
19	1	141.7	0.59	142.02	1.06
19	2	143.4	1.24	143.81	1.39
19	3	151.9	2.37	153.29	1.69
19	4	154.4	4.89	154.14	2.68
19	5	160.7	1.67	162.72	2.08
19	6	144.0	1.52	143.55	1.26
19	7	151.5	1.44	151.45	2.63
19	8	169.0	1.75	168.56	1.93
19	9	137.9	0.36	140.29	1.23
19	10	166.4	0.75	167.69	2.58
OVER-ALL AVE.		153.07		154.24	

TABLE 4 CONTINUED

SUMMARY OF CONSECUTIVE B.D.V. TESTS FOR INDIVIDUAL XD-3B DIODES

All Tests with Diodes in Total Darkness

Rack No.	Diode No.	Ave. for First 10 Firings: Mean B.D.V.	Ave. for First 10 Firings: Std. Deviation (Sigma)	Ave. for Second 10 Firings: Mean B.D.V.	Ave. for Second 10 Firings: Std. Deviation (Sigma)
11	1	227.24	0.28	227.99	0.63
11	2	221.11	1.26	221.07	1.45
11	3	230.07	2.14	239.14	1.89
11	4	229.52	0.78	229.62	2.21
11	5	231.74	0.40	232.21	1.41
11	6	238.79	0.35	239.64	0.69
11	7	241.99	0.94	242.32	1.41
11	8	243.64	0.97	246.32	0.57
11	9	228.53	0.50	229.79	0.63
11	10	237.72	0.20	239.48	0.76
13	1	222.9	0.46	224.73	1.12
13	2	228.2	0.43	229.13	1.08
13	3	229.0	0.91	229.72	1.18
13	4	235.3	0.42	237.21	1.45
13	5	237.0	3.15	236.72	1.19
13	6	238.4	3.60	238.71	1.61
13	7	236.4	1.99	236.10	0.43
13	8	232.1	1.52	233.08	0.58
13	9	230.0	0.73	232.50	1.72
13	10	239.7	0.89	240.59	0.43
16	1	239.3	0.74	241.10	2.18
16	2	236.3	2.19	239.03	2.45
16	3	224.5	0.81	226.79	3.55
16	4	237.9	1.53	239.22	0.48
16	5	230.7	0.77	235.47	1.39
16	6	219.8	0.38	220.51	0.75
16	7	223.9	1.24	224.45	0.63
16	8	234.0	1.48	234.73	1.24
16	9	230.4	0.39	232.64	0.69
16	10	242.8	0.55	242.70	1.22
OVER-ALL AVE.		232.90		234.09	

TABLE 4 CONTINUED

SUMMARY OF CONSECUTIVE BREAKDOWN VOLTAGE TESTS
ANALYSIS OF VARIANCE

VARIANCE		TUBE TYPE XD-1B	TUBE TYPE XD-2B	TUBE TYPE XD-3B
σ_1^2	First 10 Days	15.24 (VOLT)^2	1.96 (VOLT)^2	0.018 (VOLT)^2
	Second 10 Days	5.94	4.34	0.020
σ_2^2	First 10 Days	36.89	51.63	43.10
	Second 10 Days	32.50	49.04	43.87
σ_0^2	First 10 Days	6.85	3.97	1.79
	Second 10 Days	17.34	5.14	1.94
	MEANS			
	First 10 Days	103.29 VOLTS	153.07 VOLTS	232.90 VOLTS
	Second 10 Days	103.52	154.24	234.09

NOMENCLATURE

σ_1^2: An average individual diode exhibits this variance on successive breakdowns, due to changing breakdown voltage (a physical reason) and/or change in experimental environment.

σ_2^2: For an average measurement, this is the variance due to the fact that the diodes differ from one another.

σ_0^2: Residual Variance: Not attributable to above causes. can be considered as variance due to chance.

*: The small value of σ_1^2 for the XD-3B diodes is of no statistical significance. In fact, σ_1^2 should be combined with σ_0^2 in this case and the total should be considered as the variance due to an individual (average) diode.

TABLE 5

COMPARISON OF B.D.V. TESTS ON G.E. COLD CATHODE TYPES XD-1B, 2B AND 3B

COMPARING THE MEAN AND STANDARD DEVIATION ON PREPRODUCTION SAMPLES TESTED DURING AUG-SEPT 1950 -VS- PILOT LOT PRODUCTION SAMPLES RECEIVED FROM N.O.P. ON 12-19-51 AND TESTED DEC-JAN 1951-1952

All the Tests Were Run With the Diodes in Total Darkness.

Tube Type	Ave. Arithmetic Mean B.D.V. Preproduction Samples	Ave. Arithmetic Mean B.D.V. Pilot Production Samples	Comment	Ave. Standard Deviation Preproduction Samples	Ave. Standard Deviation Pilot Production Samples	Comment
XD-1B	101.86 volts	102.15 volts	(a)	± 4.29 volts	± 6.54 volts	(d)
XD-2B	150.08 "	154.82 "	(b)	7.66 "	8.03 "	(e)
XD-3B	229.04 "	231.72 "	(c)	10.44 "	6.70 "	(f)

Comments:

(a) No significant difference compared by "t-test," Brownlee, K. A. "Industrial Experimentation," 1947
(b) Significantly different " " " " " " "
(c) " " " " " " " " "
(d) " " " Variance Ratio test: " " " "
(e) No significant difference " " " " " " " "
(f) Significantly different " " " " " " " "

Note: Fifty diodes of each type of the preproduction samples were each fired three times consecutively in the positive direction followed by three breakdowns in the negative direction.

Sixty diodes of the XD-1B and 3B, and 200 of the 2B type of the pilot lot production samples were each fired four times consecutively in alternate directions starting with the positive polarity.

TABLE 6

REJECT RATE ON CHARGE TIME TESTS

Definition: A measurement is considered as a reject if the 0.1 microfarad condenser fails to charge to 45 Volts within 500 microseconds. (60 diodes of each type used for test.)

TUBE TYPE	VOLTAGE APPLIED	% OVERVOLTAGE	NUMBER OF READINGS	NUMBER OF REJECTS	% REJECTS
XD-1B	130 VOLTS	30%	800	9	1.5%
	120 VOLTS	20%	600	56	9.3%
XD-2B	195 VOLTS	30%	600	18	3.0%
	180 VOLTS	20%	600	60	10.0%
XD-3B	295 VOLTS	31.1%	600	5	0.8%
	270 VOLTS	20%	600	27	4.5%

TABLE 7

CHARGING VOLTAGES USED FOR EACH TUBE TYPE
CHARGE TIME TESTS

TUBE TYPE	NOMINAL BREAKDOWN VOLTAGE	APPLIED VOLTAGE	% OVERVOLTAGE
XD-1B	100 VOLTS	120 V	20
		122	22
		124	24
		126	26
		128	28
		130	30
XD-2B	150 VOLTS	180 V	20
		183	22
		186	24
		189	26
		192	28
		195	30
XD-3B	225 VOLTS	270 V	20
		275	22.2
		280	24.4
		285	26.7
		290	28.9
		295	31.1

TABLE 8

COMPARISON OF BREAKDOWN TIME WITH CHARGE TIME
COMPARISON AT EIGHTIETH PERCENTILE

TUBE TYPE	VOLTAGE APPLIED	BREAKDOWN TIME EIGHTIETH PERCENTILE	CHARGE TIME EIGHTIETH PERCENTILE	CHARGE TIME MINUS BREAK-DOWN TIME	NUMBER OF TIME CONSTANTS RC=75 MICRO-SECONDS
XD-1B	130 V	117 μ SECONDS	300 μ SECONDS	183 μ SECONDS	2.44
XD-2B	195 V	135 "	225 "	90 "	1.20
XD-3B	295 V	107 "	175 "	68 "	0.91

TABLE 9

BREAKDOWN VOLTAGE DATA
DYNAMIC BREAKDOWN VOLTAGE TESTER
Minimum voltage gradient: 8.6 volts per second
ANALYSIS OF VARIANCE
Comparison with Edison Tester results

	TUBE TYPE								
	XD-1B			XD-2B			XD-3B		
VARIANCE	A	B	C	A	B	C	A	B	C
σ_1^2 $(VOLT)^2$	15.24	5.94	0.195	1.96	4.34	1.37	0.018	0.020	0.509
σ_2^2 "	36.89	32.50	26.16	51.63	49.04	91.67	43.10	43.87	125
σ_0^2 "	6.85	17.34	0.748	3.97	5.14	3.96	1.79	1.94	1.34

A- Represents 30 diodes (of each type) tested for 10 days each on Edison Tester.
B- Represents same diodes as in A tested for 10 days each on Edison Tester after helipot had been replaced.
C- Represents 10 diodes (of each type) selected at random from the 30 tested under A and B, tested for 10 days each on DBVT.
NOMENCLATURE: Same as in Table V

TABLE 10

COMPARISON OF RESULTS OF XD-1B BREAKDOWN VOLTAGE TESTS.
FOR EDISON TESTER AND DBVT
DBVT: Pure exponential, about 10 volts per second gradient

RACK NO.	DIODE NO.	EDISON TESTER FIRST 10 DAYS		EDISON TESTER SECOND 10 DAYS		DBVT		Is the mean from the DBVT SIGNIFICANTLY different from both the means from Edison tests*
		MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	
7 —	1	97.5	3.24	100.9	5.10	97.8	2.43	NO
	2	103.9	3.91	104.2	7.20	103.3	0.79	NO
	3	93.6	2.91	96.9	6.11	91.7	0.41	NO
	4	99.4	4.73	102.3	4.23	97.3	1.45	NO
	5	115.2	6.04	117.1	5.08	110.4	2.36	NO
	6	101.4	3.46	101.1	5.65	100.0	0.05	NO
	7	109.4	6.22	110.4	4.80	105.3	0.26	NO
	8	104.9	4.99	106.1	5.28	103.0	0	NO
	9	105.3	6.87	103.0	4.73	98.0	0.28	YES

* TESTED BY STUDENT'S t-TEST; 5% SIGNIFICANCE LEVEL

TABLE 11-1

COMPARISON OF RESULTS OF XD-2B BREAKDOWN VOLTAGE TESTS
FOR EDISON TESTER AND DBVT
DBVT: Pure exponential, about 10 volts per second gradient.

RACK NO.	DIODE NO.	EDISON TESTER FIRST 10 DAYS		EDISON TESTER SECOND 10 DAYS		DBVT		Is the mean from the DBVT SIGNIFICANTLY different from both the means from Edison tests?*	
		MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)		
19 –	1	147.7	0.59	142.0	1.06	141.4	1.18	NO	
	2	143.4	1.24	143.8	1.39	142.3	1.25	NO	
	3	151.9	2.37	153.5	1.69	148.9	2.76		YES
	4	154.4	4.89	154.1	2.68	151.4	5.27	NO	
	5	160.7	1.67	162.7	2.08	159.4	3.44	NO	
	6	144.0	1.52	143.8	1.26	142.1	1.20		YES
	7	151.5	1.44	151.5	2.63	149.7	0.95	NO	
	8	169.0	1.75	168.6	1.93	164.1	0.99		YES
	9	137.9	0.36	140.3	1.23	138.0	0.0	NO	
	10	166.4	0.75	167.7	2.58	164.1	0.32		YES

* TESTED BY STUDENT'S t-TEST; 5% SIGNIFICANCE LEVEL.

TABLE II-2

COMPARISON OF RESULTS OF XD-3B BREAKDOWN VOLTAGE TESTS FOR EDISON TESTER AND DBVT

DBVT: Pure exponential, about 10 volts per second gradient

RACK NO.	DIODE NO.	EDISON TESTER FIRST 10 DAYS		EDISON TESTER SECOND 10 DAYS		DBVT		Is the mean from the DBVT SIGNIFICANTLY different from both the means from Edison tests?*	
		MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)	STANDARD DEVIATION (VOLTS)		
16-	1	239.3	0.74	241.1	2.18	243.0	3.22	NO	
	2	236.3	2.19	239.0	2.45	244.7	1.49		YES
	3	224.5	0.81	226.8	3.55	223.4	0.84		YES
	4	237.9	1.53	239.2	0.48	241.0	1.33		YES
	5	230.7	0.77	235.5	1.39	236.0	0.67	NO	
	6	219.8	0.38	220.5	0.75	217.9	0.32		YES
	7	223.9	1.24	224.5	0.63	221.5	0.53		YES
	8	234.0	1.48	234.7	1.24	231.0	.0		YES
	9	230.4	0.59	232.6	0.69	232.4	0.97	NO	
	10	242.8	0.55	242.7	1.22	244.7	0.48		YES

* TESTED BY STUDENT'S t-TEST; 5% SIGNIFICANCE LEVEL.

TABLE II-3

COMPARISON OF RESULTS OF BREAKDOWN VOLTAGE TESTS FOR EDISON AND DBVT: PURE EXPONENTIAL, APPROX. 10 VOLTS PER SECOND.

MEAN BREAKDOWN VOLTAGE FOR ALL DIODES TESTED WITH BOTH TESTERS

TUBE TYPE	NUMBER OF DIODES	EDISON TESTER FIRST 10 DAYS	EDISON TESTER SECOND 10 DAYS	DBVT
XD-1B	9	103.40 VOLTS	104.67 VOLTS	100.76 VOLTS
XD-2B	10	152.09 VOLTS	152.78 VOLTS	150.14 VOLTS
XD-3B	10	231.96 VOLTS	233.69 VOLTS	233.56 VOLTS

TABLE 11-A

ANALYSIS OF VARIANCE
COMPARISON OF RESULTS OF:

1. EDISON TESTER - FIRST 10 DAYS.
2. EDISON TESTER - SECOND 10 DAYS.
3. DBVT - NO VOLTAGE STEP APPLIED
4. DBVT - 70 VOLT STEP APPLIED INITIALLY.

VARIANCE	TEST	TUBE TYPE		
		XD-1B	XD-2B	XD-3B
σ_1^2 (VOLTS)^2	1. EDISON - FIRST 10 DAYS	15.24	1.96	0.018
	2. EDISON - SECOND 10 DAYS	5.94	4.34	0.020
	3. DBVT - NO VOLTAGE STEP	0.195	1.37	0.509
	4. DBVT - 70 VOLT STEP	2.83	0.414	*
σ_2^2 (VOLTS)^2	1. EDISON - FIRST 10 DAYS	36.89	51.63	43.10
	2. EDISON - SECOND 10 DAYS	32.50	49.04	43.87
	3. DBVT - NO VOLTAGE STEP	26.16	91.67	125
	4. DBVT - 70 VOLT STEP	36.41	50.68	*
σ_0^2 (VOLTS)^2	1. EDISON - FIRST 10 DAYS	6.85	3.87	1.79
	2. EDISON - SECOND 10 DAYS	17.34	5.14	1.94
	3. DBVT - NO VOLTAGE STEP	0.748	3.96	1.34
	4. DBVT - 70 VOLT STEP	2.09	1.63	*

* DATA EXHIBITS A BI-MODAL TENDENCY FOR BREAKDOWN VOLTAGE CHARACTERISTIC.

TABLE 12

COMPARISON OF MEANS FOR DBVT
(a) WITHOUT VOLTAGE STEP
(b) WITH 70 VOLT STEP APPLIED INITIALLY

RACK NO.	DIODE NO.	DBVT: WITHOUT VOLTAGE STEP		DBVT: WITH 70 VOLT STEP APPLIED INITIALLY		$t = \frac{\lvert\bar{X}_1 - \bar{X}_2\rvert}{\sigma}\sqrt{\frac{N_1 N_2}{N_1 + N_2}}$ (SEE NOTE BELOW)
		MEAN, $\bar{X}_1$, VOLTS	STANDARD DEVIATION, σ_1, VOLTS	MEAN, $\bar{X}_2$, VOLTS	STANDARD DEVIATION, σ_2, VOLTS	18 DEGREES OF FREEDOM.
7 –	1	97.8	2.43	95.4	0.66	3.01
	2	103.3	0.79	100.0	1.76	5.40
	3	91.7	0.41	87.5	2.17	6.00
	4	97.3	1.45	91.6	2.80	5.68
	5	110.4	2.36	104.7	3.82	4.00
	6	100.0	0.05	94.5	3.49	4.98
	7	105.3	0.26	104.5	0.60	3.89
	8	103.0	0	103.2	0.24	6.70
	9	98.0	0.28	95.6	0.96	7.02

NOTE: THE SIZE OF t IS THE CRITERION FOR COMPARISON OF MEANS
$\lvert\bar{X}_1 - \bar{X}_2\rvert$ = ABSOLUTE VALUE OF DIFFERENCE BETWEEN MEANS.

σ = WEIGHTED UNBIASED ESTIMATE OF STANDARD DEVIATION:

$$\sigma^2 = \frac{\sigma_1^2 + \sigma_2^2}{N_1 + N_2 - 1}$$

$N_1 = N_2 = 10$

FOR $N_1 + N_2 - 2 = 18$ DEGREES OF FREEDOM

(CONTINUED)

TABLE 13

TABLE 13 CONTINUED

PROBABILITY OF HAVING THIS LARGE A DIFFERENCE BETWEEN MEANS BY CHANCE ALONE.	t
10%	1.73
5%	2.10
2%	2.55
1%	2.88
0.1%	3.92

THUS WE SEE THAT THE MEAN BREAKDOWN VOLTAGE RECORDED FOR A GIVEN DIODE IN THE TESTS WITH THE 70 VOLT STEP INITIALLY APPLIED IS SIGNIFICANTLY SMALLER THAN THE MEAN BREAKDOWN VOLTAGE WITHOUT THE 70 VOLT STEP APPLIED.

TABLE 13-A

BREAKDOWN VOLTAGE TESTS ON SHIELDED DIODES.
TEST MADE ON EDISON TESTER
TEN READINGS ON EACH DIODE

A-SHIELD POSITIVE

	GROUP 1: HIGH VOLTAGE REJECTS; EXHAUST MACHINE NO.1		GROUP 2: HIGH VOLTAGE REJECTS; EXHAUST MACHINE NO. 2		GROUP 3: NEW DIODES, NEW EXHAUST MACHINE	
DIODE	MEAN, VOLTS	σ, VOLTS	MEAN, VOLTS	σ, VOLTS	MEAN, VOLTS	σ, VOLTS
1	103.50	0.24	91.58	0.26	90.11	0.48
2	95.00	0.27	98.57	0.26	96.15	0.42
3	101.80	0.32	99.24	0.18	95.46	0.28
4	95.80	0.21	97.03	0.29	94.09	0.33
5	94.16	0.67	94.39	0.34	90.53	0.32
6	99.23	0.18	97.01	0.43	96.03	0.24
7	98.31	0.22	98.58	0.25	93.52	0.24
8	99.29	0.80	100.59	0.25	92.81	0.42
9	94.90	0.35	98.27	0.34	94.08	0.37
10	96.97	0.47	——	——	93.30	0.30
SUMMARY	97.90		97.25		93.61	

B-SHIELD NEGATIVE

DIODE	MEAN, VOLTS	σ, VOLTS	MEAN, VOLTS	σ, VOLTS	MEAN, VOLTS	σ, VOLTS
1	126.89	0.18	109.58	0.08	114.35	0.10
2	108.73	3.90	126.14	0.12	117.71	0.28
3	119.56	0.48	125.11	0.07	117.98	0.06
4	108.24	0.08	120.89	0.10	115.68	0.10
5	116.06	0.50	123.64	0.44	113.63	0.19
6	116.84	0.19	124.83	0.10	116.50	0.10
7	118.12	0.13	120.28	0.09	109.78	0.10
8	112.39	0.14	121.75	0.12	112.52	0.08
9	106.18	0.17	121.83	0.13	115.12	0.18
10	125.03	0.20	——	——	112.99	0.08
SUMMARY	115.80		121.56		114.63	

TABLE 14

MEAN BREAKDOWN VOLTAGE FOR DIFFERENT VOLTAGE GRADIENTS
XD-1B

Gradient / Rack Diode	8.6 V. Per Second	Significant Difference	86 V. Per Second	Significant Difference	860 V. Per Second	Significant Difference	8600 Per Second	Significant Difference	86000V Per Second
21 - 1	106.88 V.		106.75 V.	✓	108.63 V.	✓	112.20 V.	✓	118.13 V.
2	100.50	✓	102.13	✓	103.88	✓	107.75		106.90
3	97.50		98.33	✓	102.10		101.88	✓	105.25
4	106.50		106.67		107.00	✓	112.50	✓	123.20
5	101.38		101.50	✓	102.50	✓	106.00	✓	108.88
6	94.75		95.90	✓	99.17	✓	101.88		103.50
7	99.20	X	98.88		100.25	✓	102.88	✓	105.13
8	101.10	X	100.75	✓	101.80	✓	105.60		106.33
9	96.60		97.75	✓	100.90	✓	104.10	✓	109.75
10	99.40	✓	99.80		100.40	✓	104.38		105.25
23 - 1	102.13		102.50		—		107.50		—
2	105.63		105.75		106.25		107.17		109.13
3	98.13	✓	99.50		—		102.83	✓	105.33
4	94.88	✓	96.20		—		99.88	✓	105.00
5	97.75		97.90		—		—		—
6	99.90	✓	102.10		102.75	✓	105.67		—
7	101.40		101.75		—		—		118.88
8	109.80		110.10		—		114.80		—
9	96.20	✓	96.80	✓	98.25	✓	100.63		—
10	92.63	✓	94.40		95.00	✓	98.10		—

* ✓ Denotes that the mean Breakdown Voltage of the Diode using the (adjacent) larger gradient is significantly higher than obtained using the adjacent smaller gradient.
X Denotes that the mean Breakdown Voltage of the Diode using the (adjacent) smaller gradient is significantly higher than that using the (adjacent) larger gradient.

The 10% level of probability is chosen as the critical level for significance.

TABLE 15

MEAN BREAKDOWN VOLTAGE FOR DIFFERENT VOLTAGE GRADIENTS
XD-2B

Gradient / Rack, Diode	9.6 V Per Second	Significant Difference *	96 V Per Second	Significant Difference	960V Per Second	Significant Difference	9600V Per Second	Significant Difference	96000V Per Second
24— 1	147.00V		148.60V		149.20V	✓	157.40V		156.00V
2	158.60	✓	161.00		161.00	✓	164.33		164.00
3	143.00		143.25		144.20	✓	154.25		—
4	153.50	✓	159.60		—		169.33		165.80
5	151.00		151.00	✓	152.20	✓	154.20	✓	160.00
6	150.00	✓	150.80	X	149.75	✓	152.20	✓	159.00
7	140.20	✓	141.80	✓	143.60	✓	149.40	✓	151.75
8	150.20		150.75		152.00	✓	156.20		157.00
9	149.40		150.20	✓	152.40	X	148.67		—
10	159.00	✓	166.60	✓	171.00	✓	174.25	✓	180.25
26— 1	147.00	✓	154.00	✓	157.00	✓	164.33	✓	170.80
2	142.20	X	141.80	✓	143.60		146.00		150.20
3	145.00		145.40	✓	147.50	✓	155.00		153.50
4	152.00	✓	156.80	✓	158.40	✓	165.00	X	161.00
5	159.00	✓	162.00	✓	163.80	✓	167.20	✓	173.00
6	149.80	X	148.60		149.20	✓	154.50	✓	159.50
7	143.00	✓	143.60	✓	145.60		146.25	✓	151.60
8	154.20		155.20		—		163.75		163.20
9	144.00	✓	153.25	✓	156.00		—		—
10	140.25	✓	144.00	✓	146.60		—		—

* See comments on Table 15.

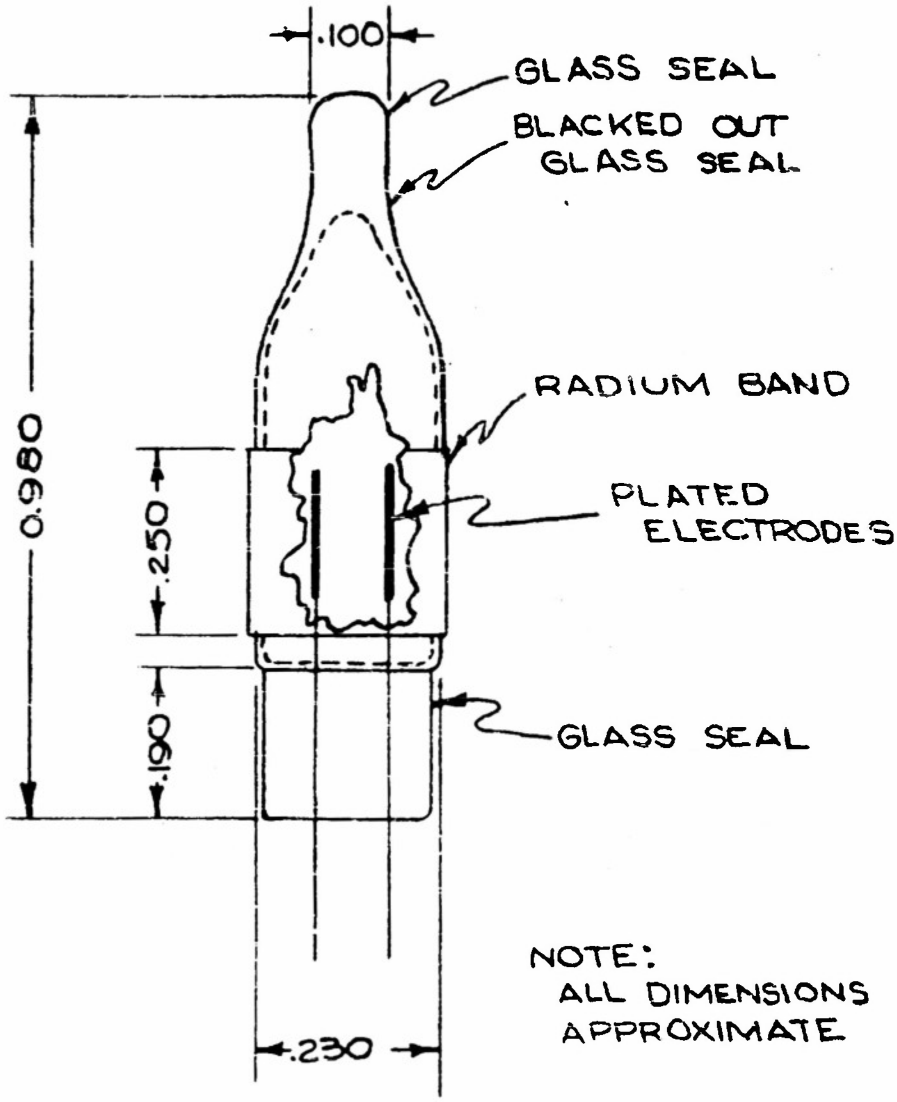
TABLE 16

MEAN BREAKDOWN VOLTAGE FOR DIFFERENT VOLTAGE GRADIENTS
XD-3B

Gradient Rack Diode	9.5V Per Second	Significant Difference	95V Per Second	Significant Difference	950V Per Second	Significant Difference	9500V Per Second	Significant Difference	95000V Per Second
27— 1	218.00V	✓	222.80V		223.80V	✓	231.50V		— V
2	236.20	✓	238.50		238.50	✓	243.00		—
3	233.40		234.20	✓	235.75	✓	239.00		—
4	228.60	✓	230.40		231.33		—		235.00
5	233.50	✓	238.00		238.40	✓	247.50		246.40
6	221.50	✓	228.40	✓	230.00	✓	231.35		233.25
7	225.25		236.00	✓	238.00	✓	241.50	✓	251.75
8	226.25	✓	234.75	✓	236.40	✓	240.50	✓	244.40
9	222.00	✓	230.40	✓	232.00	✓	240.00		239.50
10	212.50	✓	222.25	✓	224.80	✓	231.50		—
33— 1	224.00	✓	241.25	✓	243.20	✓	248.75		249.50
2	222.20	✓	223.20		—		230.00	X	226.25
3	223.25	✓	228.75		230.20	✓	241.00		240.40
4	232.50	✓	237.60		—		243.50		—
5	240.20	✓	241.60		241.75	✓	250.00		—
6	235.25	X	233.60		—		239.25		—
7	219.60	✓	221.00	✓	222.00	✓	228.75		227.50
8	224.20	✓	225.40	✓	226.60	✓	231.20		—
9	238.60	✓	241.40	✓	245.00	✓	247.20	✓	250.40
10	233.20		233.40		233.00	✓	237.50	✓	242.00

* See comments on Table 15.

TABLE 17



SKETCH OF DIODE

FIGURE 1

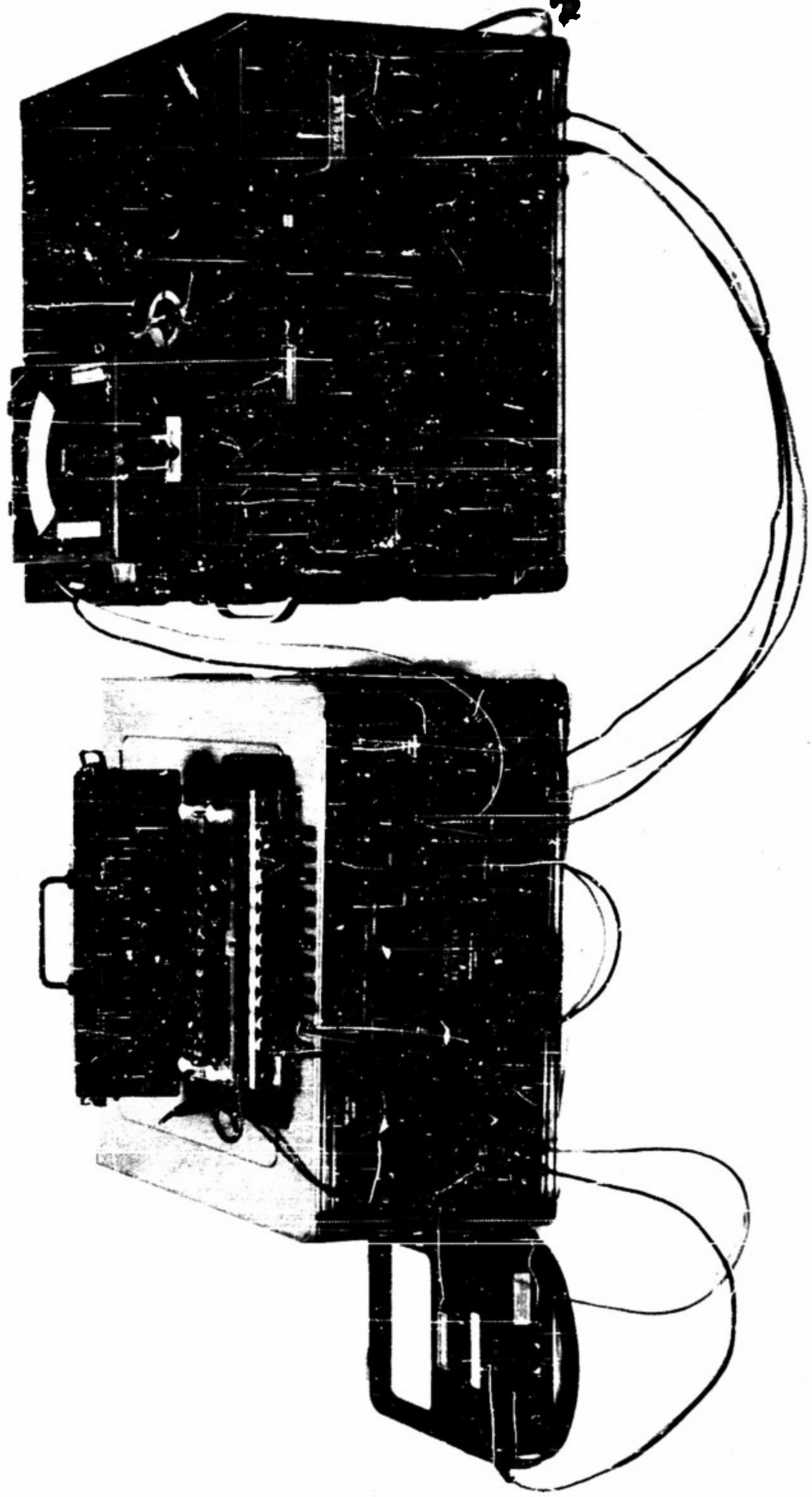
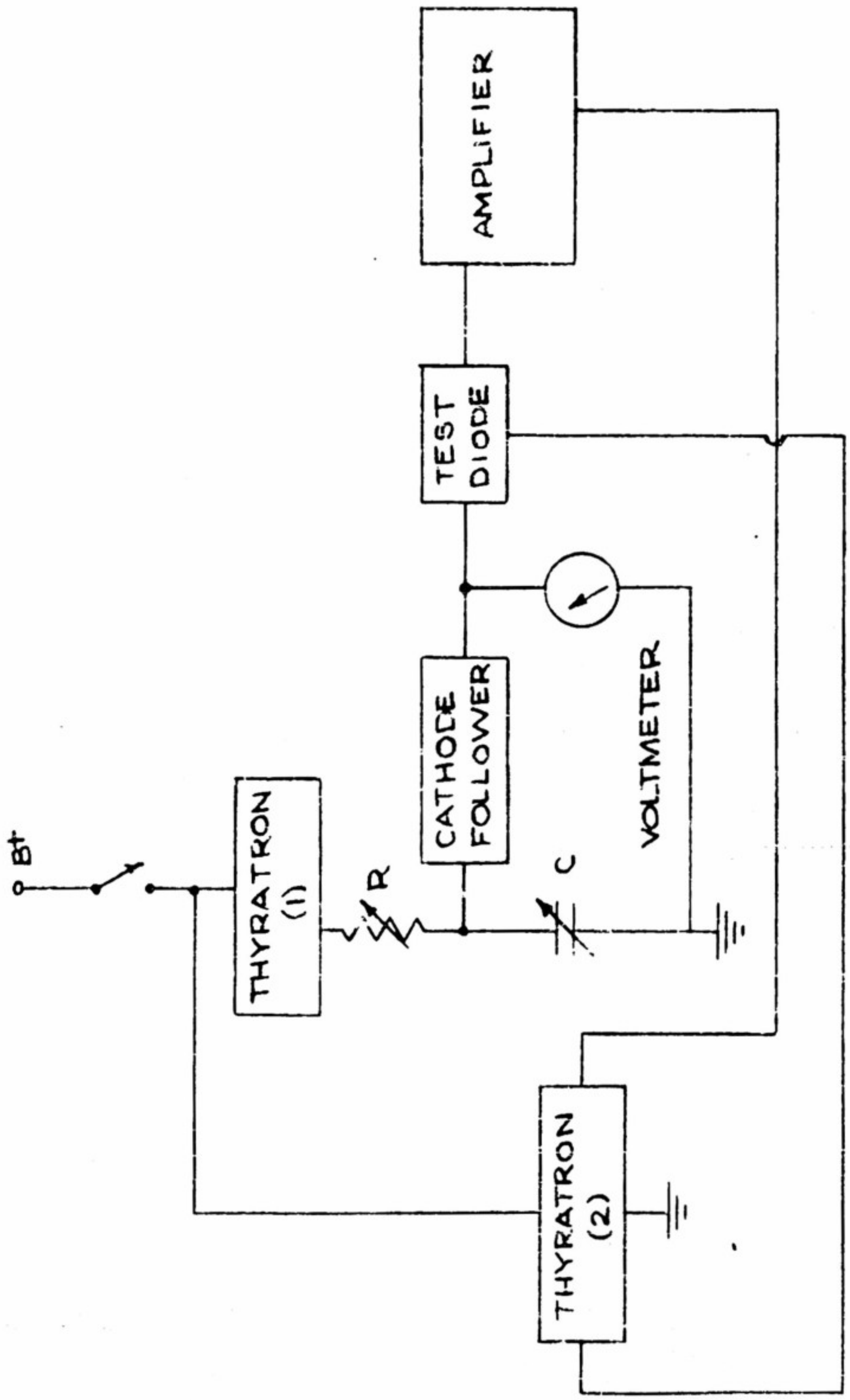


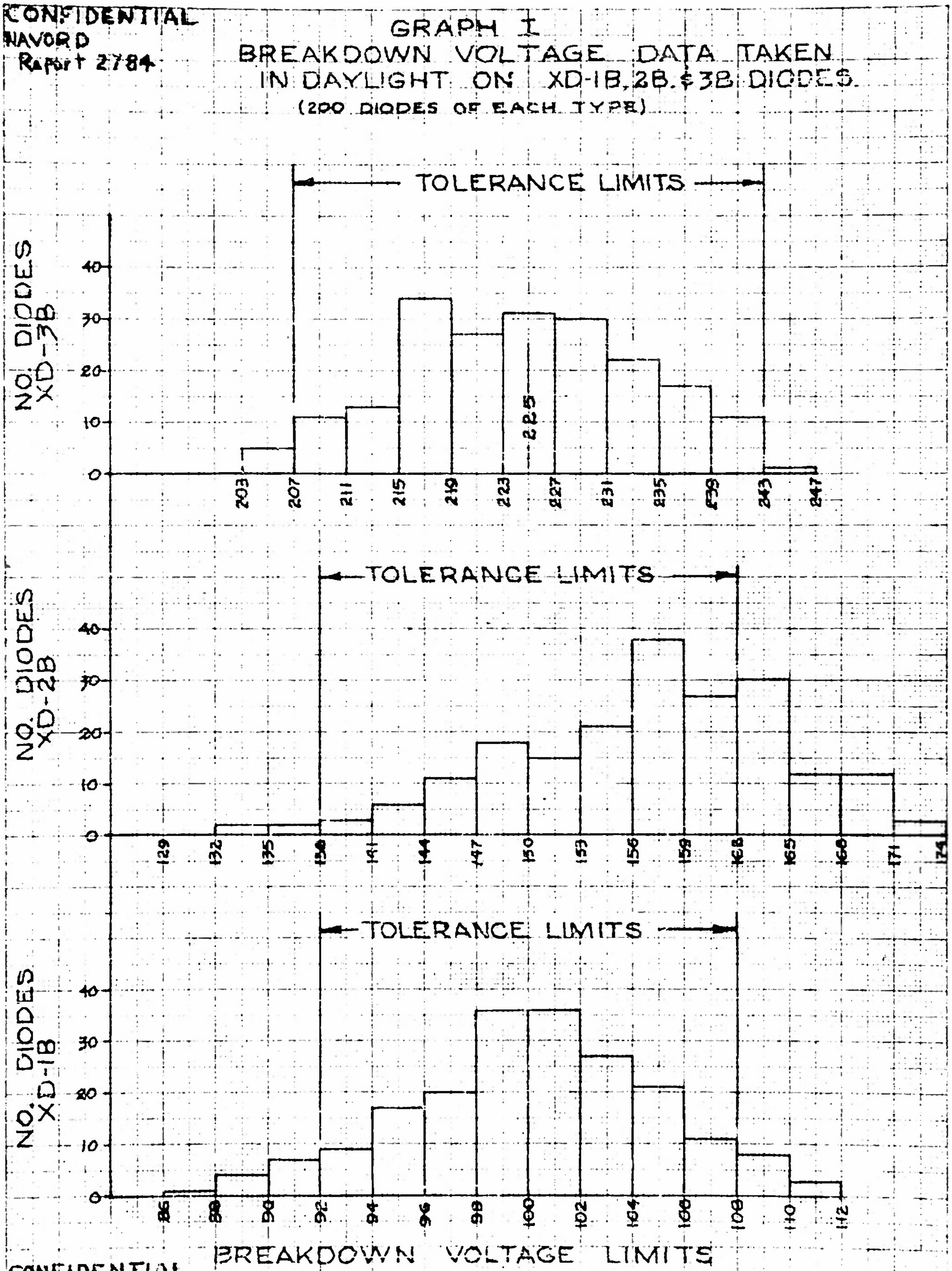
FIGURE 2



DYNAMIC BREAKDOWN VOLTAGE TESTER

FIGURE 3

CONFIDENTIAL
NAVORD
Report 2784



CONFIDENTIAL
SECURITY INFORMATION

FIGURE 4

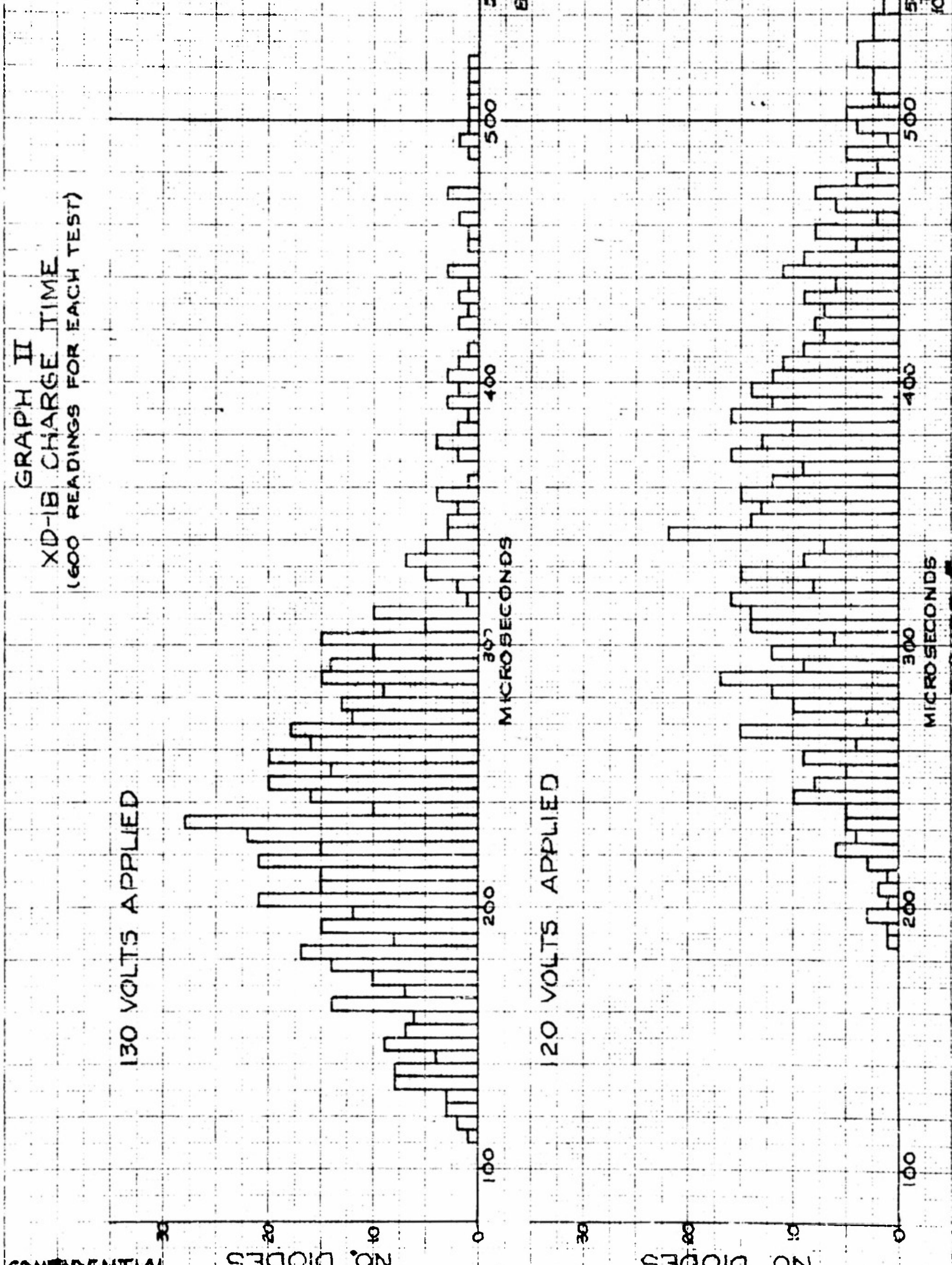

GRAPH II
XD-1B CHARGE TIME
(600 READINGS FOR EACH TEST)
130 VOLTS APPLIED
120 VOLTS APPLIED
MICROSECONDS
MICROSECONDS
NO. DIODES
NO. DIODES
100
200
300
400
500
550 TO 850
550 TO 1000
0
10
20
30

FIGURE 5

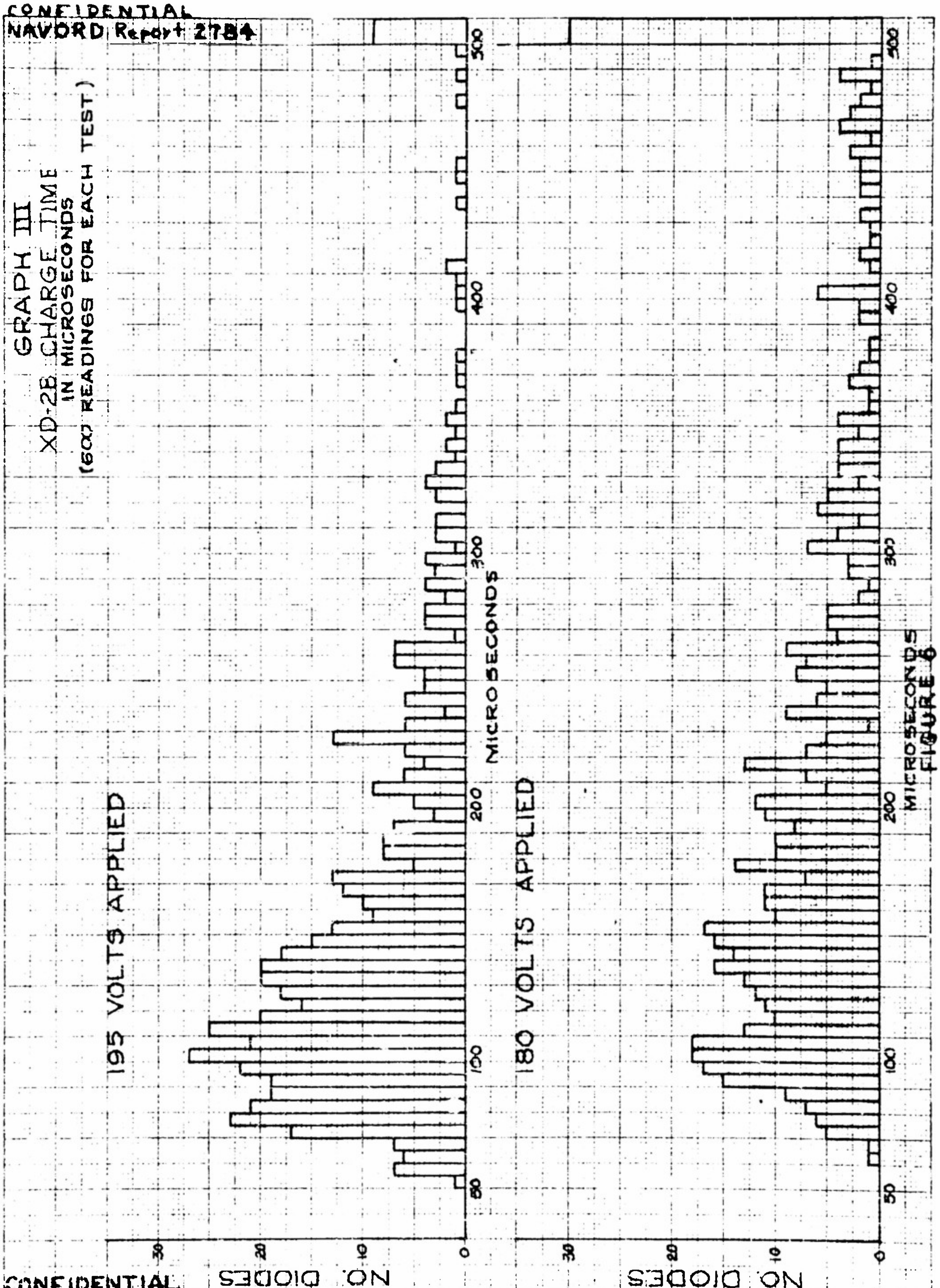

GRAPH III
XD-2B CHARGE TIME
IN MICROSECONDS
(600 READINGS FOR EACH TEST)
195 VOLTS APPLIED
180 VOLTS APPLIED
MICROSECONDS
MICROSECONDS
NO. DIODES
NO. DIODES
0
10
20
30
50
100
200
300
400
500

FIGURE 6

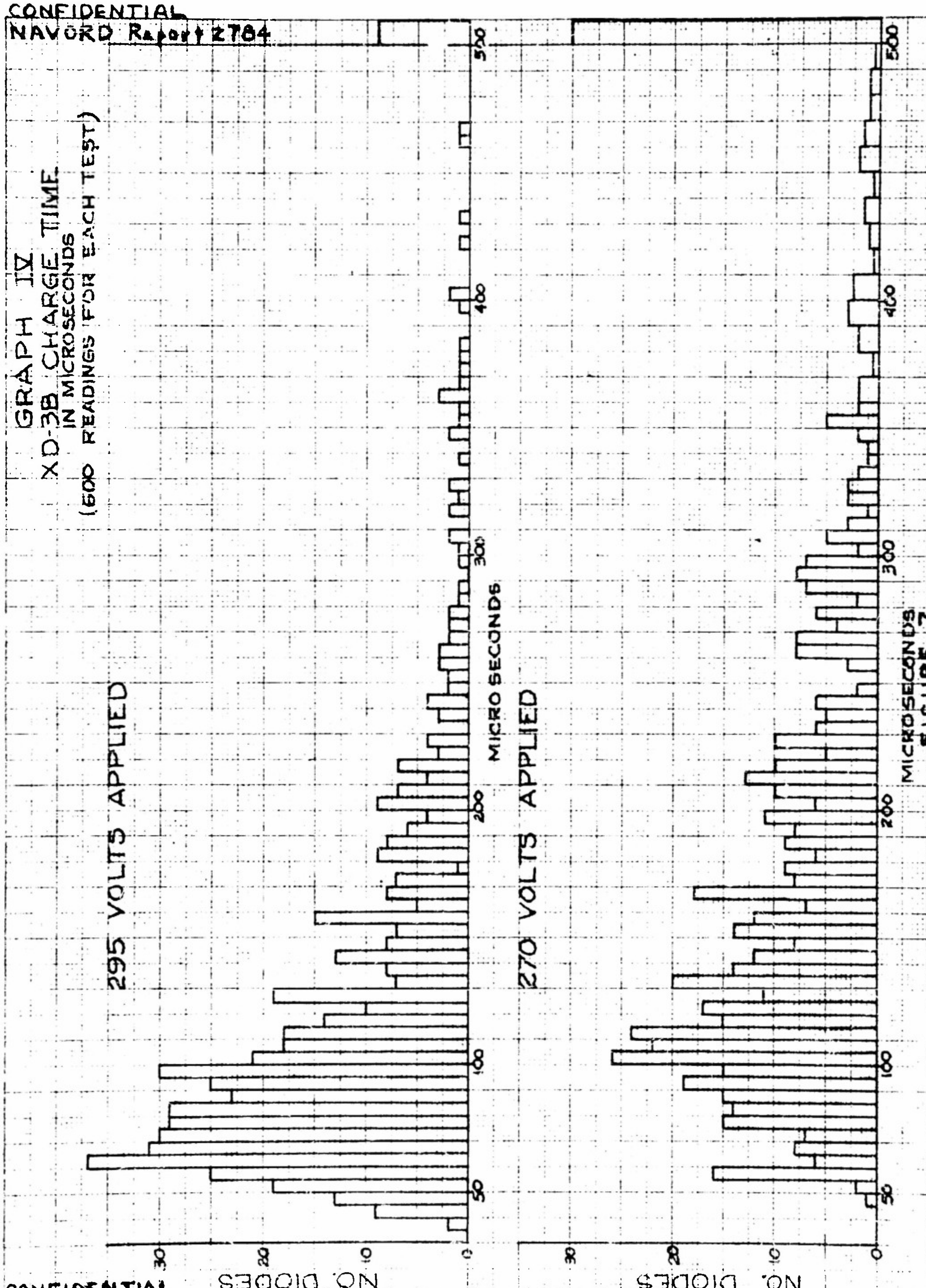

GRAPH IV
XD-3B CHARGE TIME
IN MICROSECONDS
(600 READINGS FOR EACH TEST)
295 VOLTS APPLIED
MICRO SECONDS
NO. DIODES
270 VOLTS APPLIED
MICROSECONDS
NO. DIODES
0
10
20
30
50
100
200
300
400
500

FIGURE 7

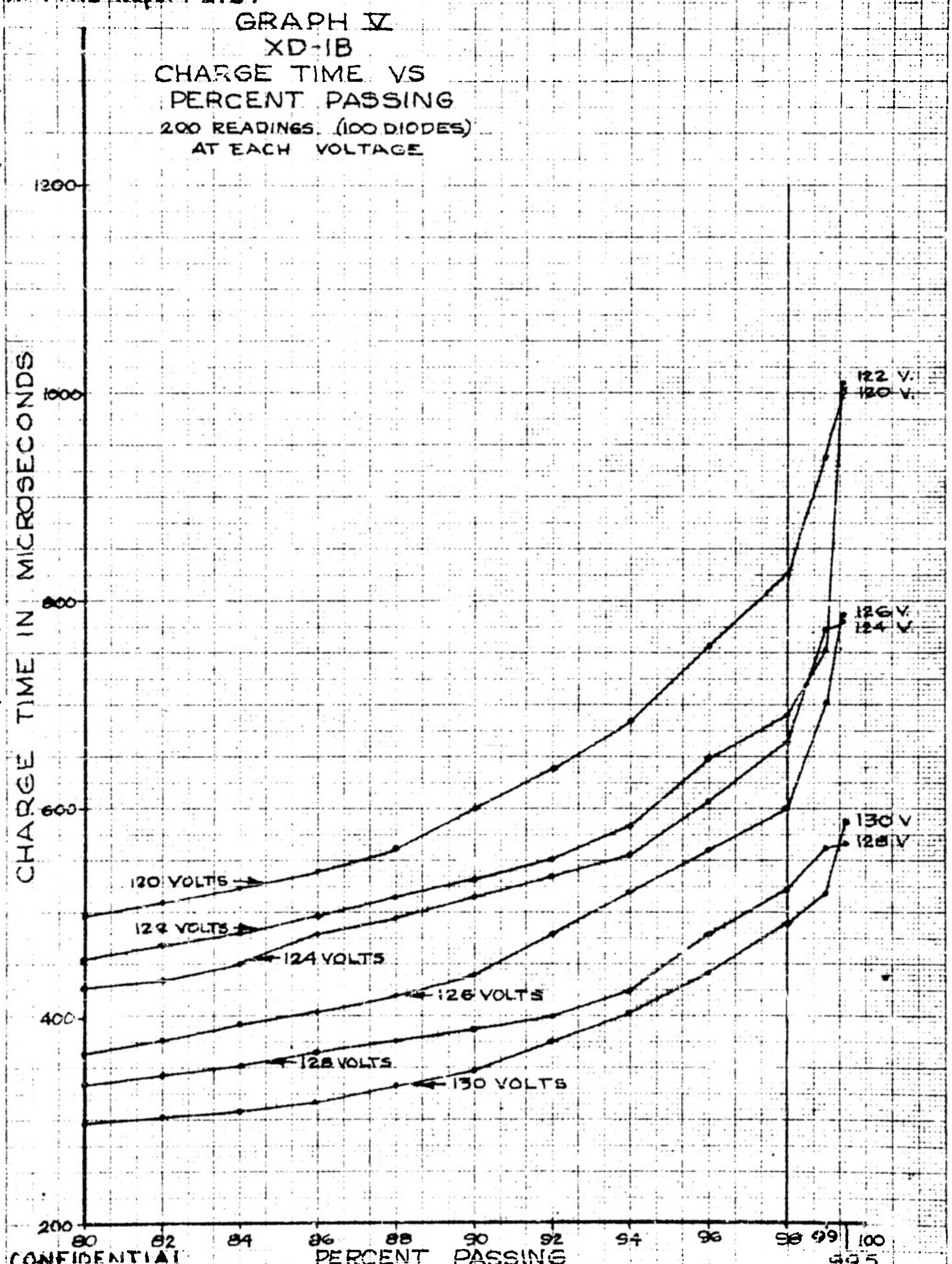

GRAPH V
XD-1B
CHARGE TIME VS
PERCENT PASSING
200 READINGS (100 DIODES)
AT EACH VOLTAGE
CHARGE TIME IN MICROSECONDS
1200
1000
800
600
400
200
120 VOLTS
122 VOLTS
124 VOLTS
126 VOLTS
128 VOLTS
130 VOLTS
122 V.
120 V.
126 V.
124 V.
130 V
128 V
80
82
84
86
88
90
92
94
96
98
99
100
99.5
PERCENT PASSING

FIGURE 8

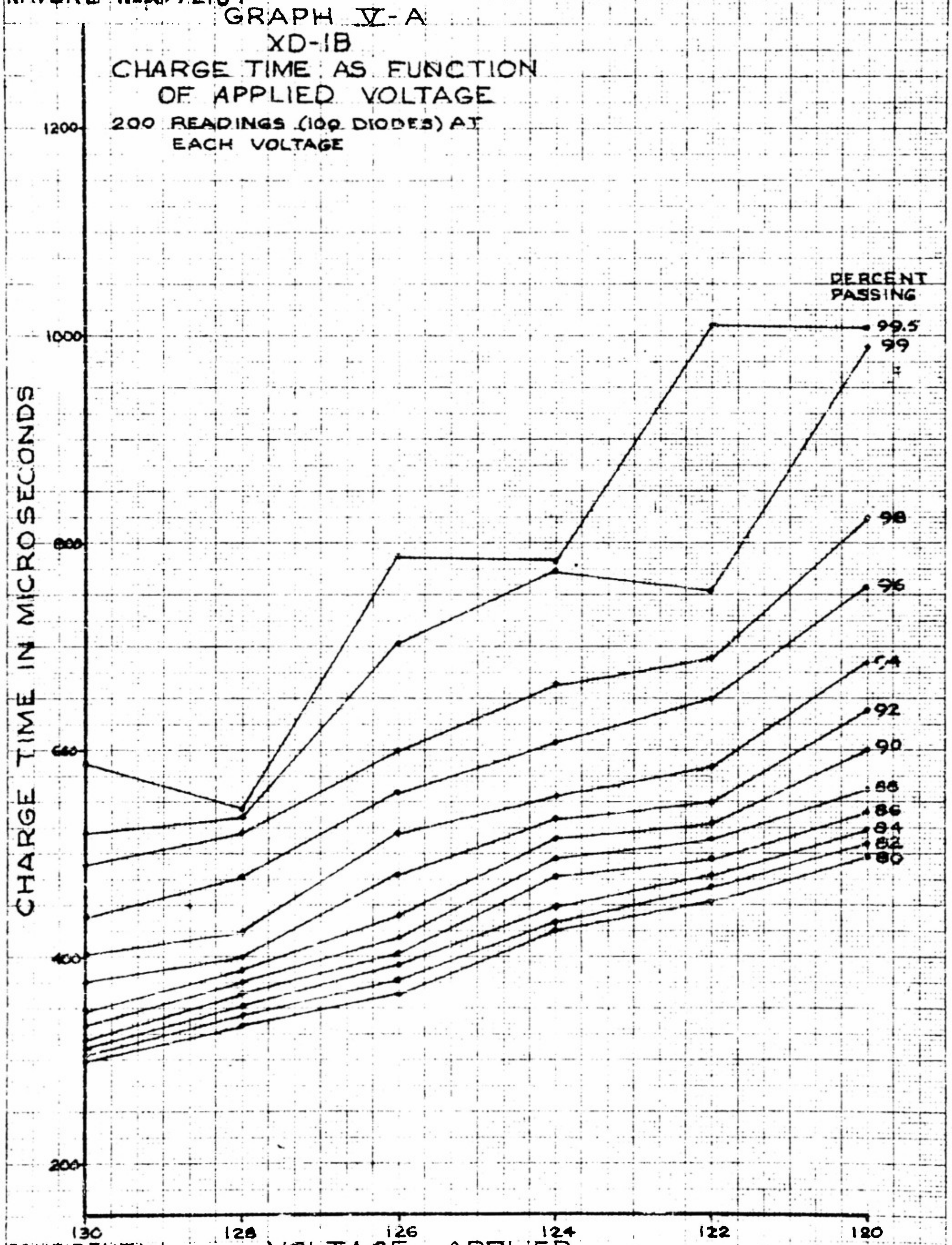

GRAPH V-A
XD-1B
CHARGE TIME AS FUNCTION
OF APPLIED VOLTAGE
200 READINGS (100 DIODES) AT
EACH VOLTAGE
CHARGE TIME IN MICROSECONDS
1200
1000
800
600
400
200
PERCENT
PASSING
99.5
99
98
96
94
92
90
88
86
84
82
80
130
128
126
124
122
120
VOLTAGE APPLIED

FIGURE 9

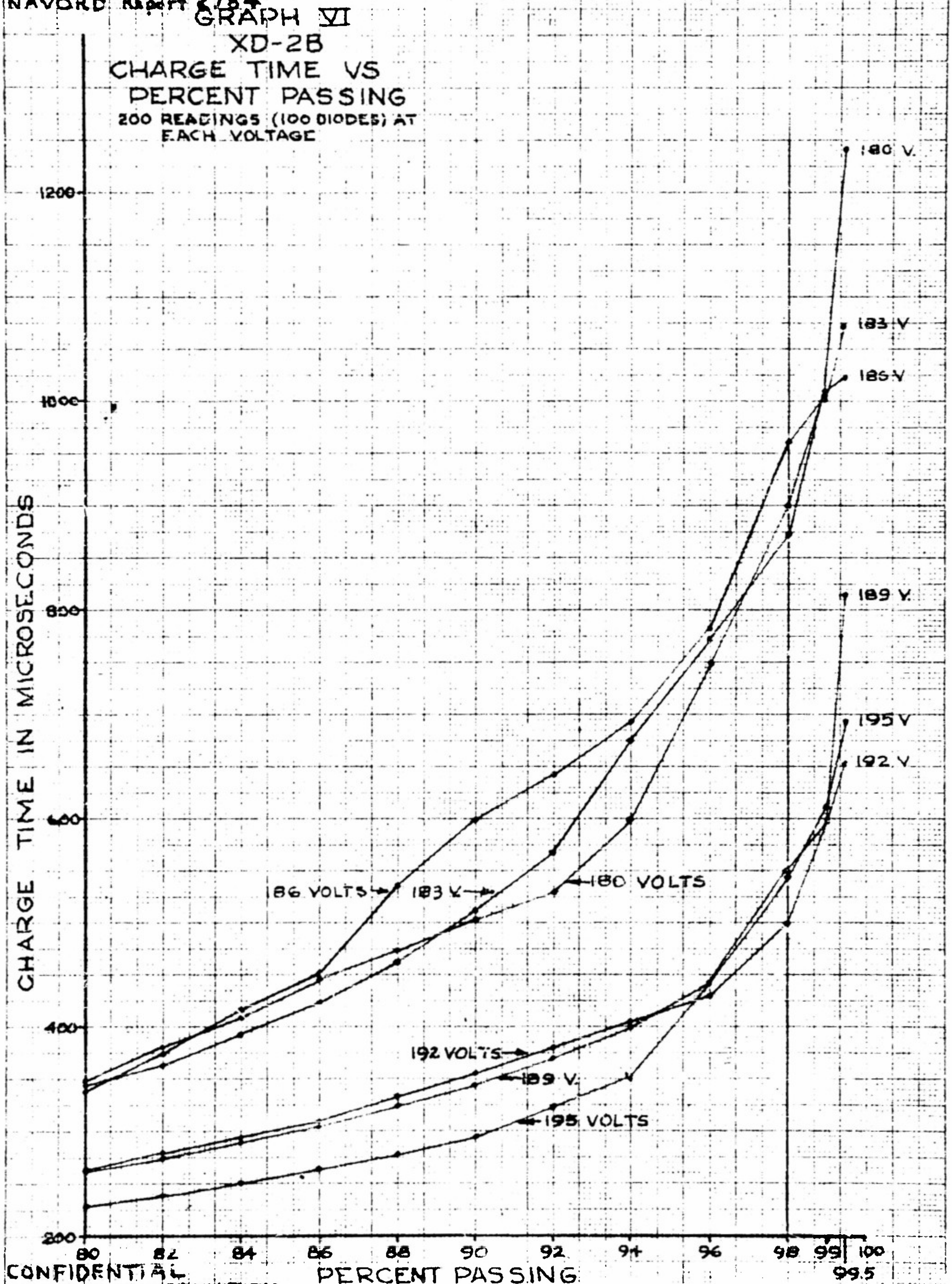

GRAPH VI
XD-2B
CHARGE TIME VS
PERCENT PASSING
200 READINGS (100 DIODES) AT
EACH VOLTAGE
180 V.
183 V
185 V
189 V.
195 V
192 V.
186 VOLTS
183 V.
180 VOLTS
192 VOLTS
189 V.
195 VOLTS
CHARGE TIME IN MICROSECONDS
1200
1000
800
600
400
200
80
82
84
86
88
90
92
94
96
98
99
100
99.5
PERCENT PASSING

FIGURE 10

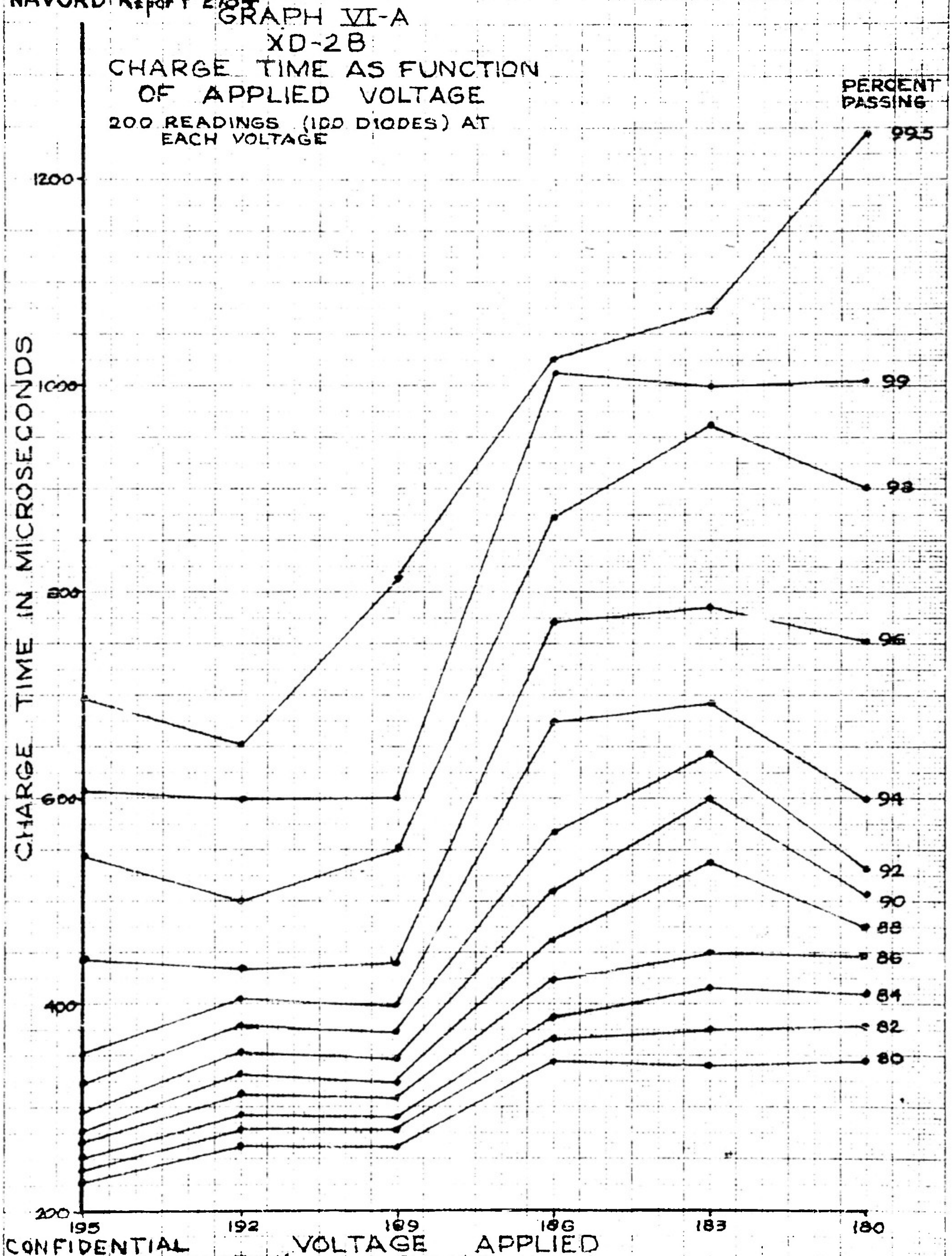

GRAPH VI-A
XD-2B
CHARGE TIME AS FUNCTION OF APPLIED VOLTAGE
200 READINGS (100 DIODES) AT EACH VOLTAGE
PERCENT PASSING
99.5
99
98
96
94
92
90
88
86
84
82
80
CHARGE TIME IN MICROSECONDS
1200
1000
800
600
400
200
195
192
189
186
183
180
VOLTAGE APPLIED

FIGURE 11

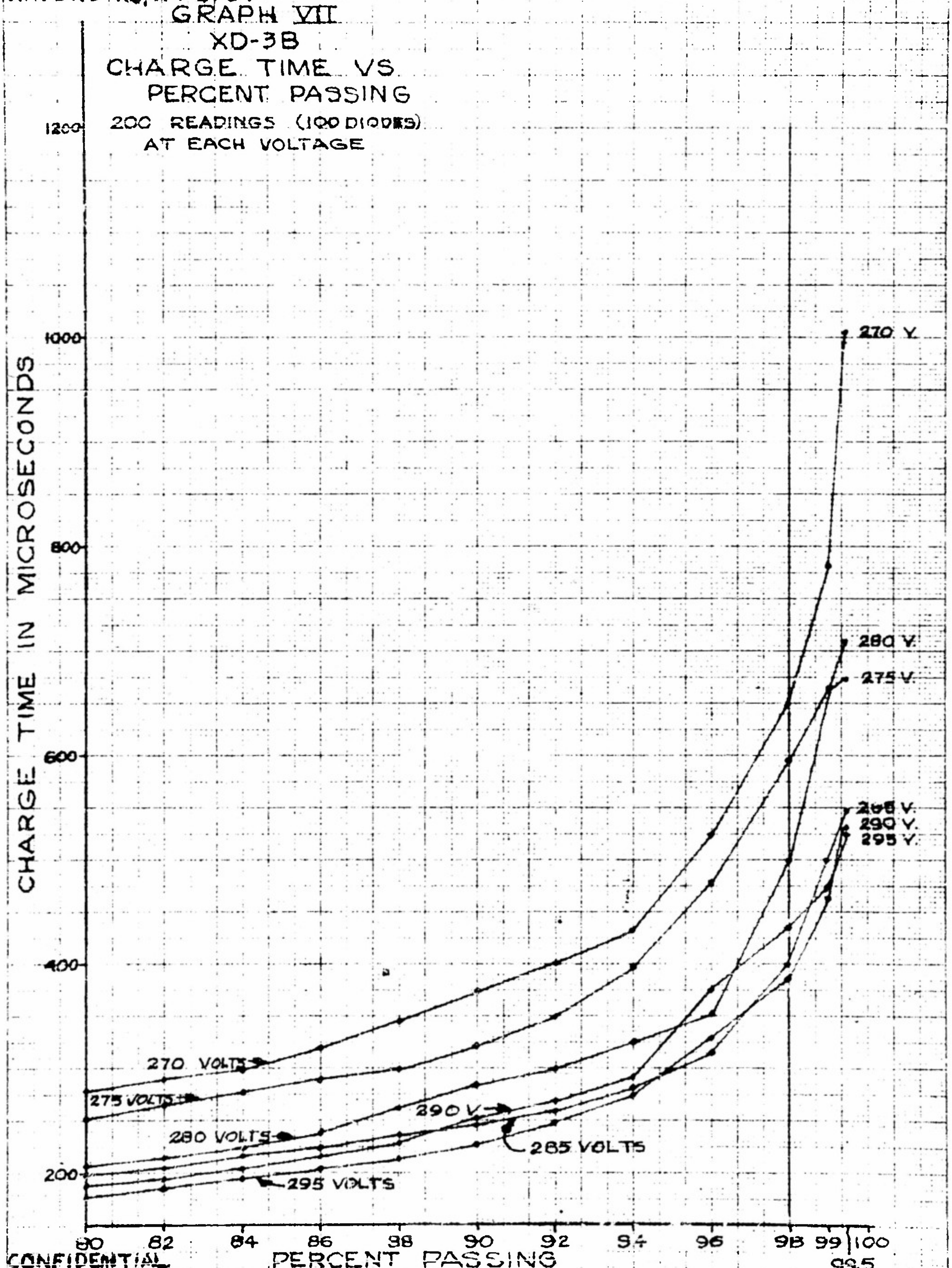
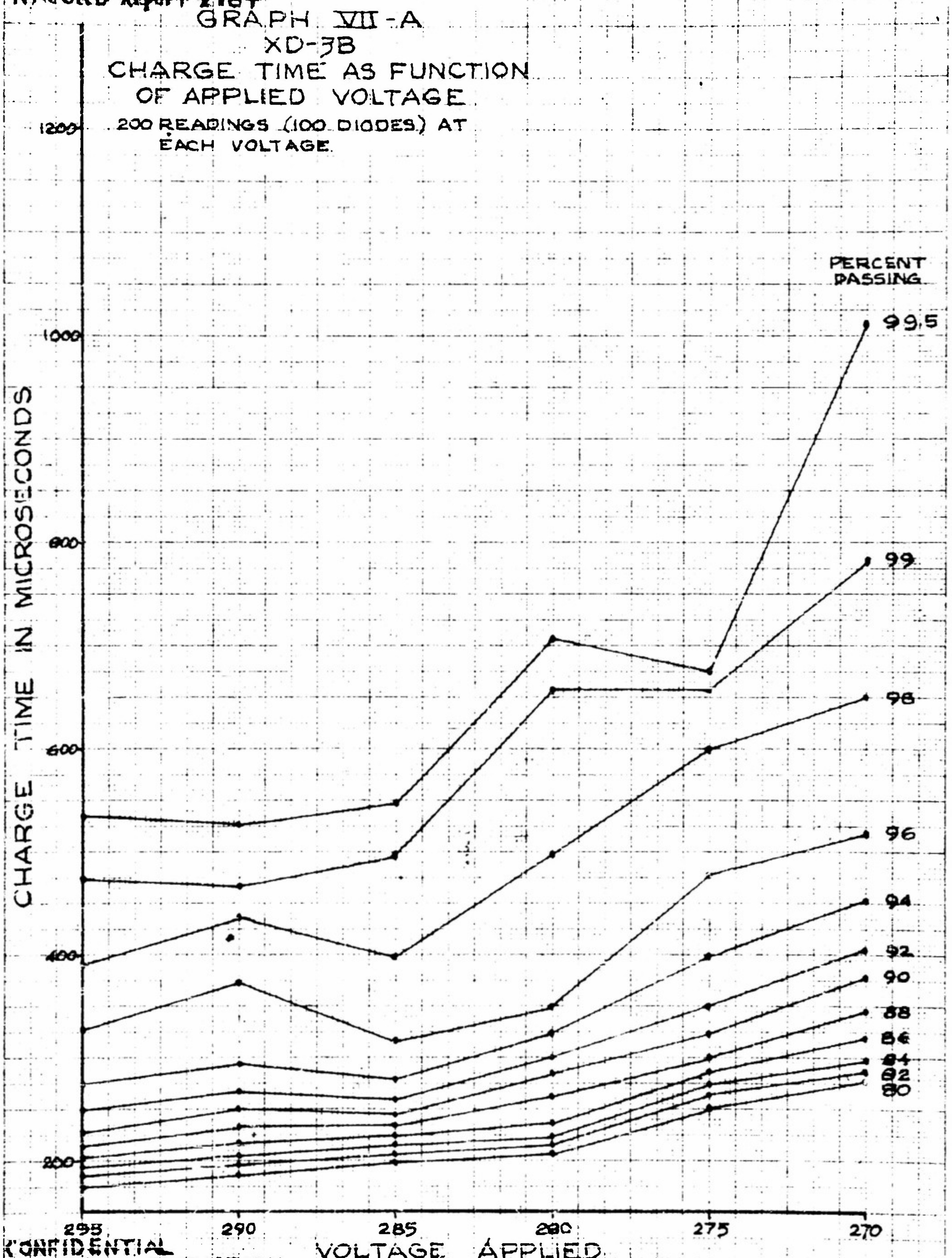

GRAPH VII
XD-3B
CHARGE TIME VS
PERCENT PASSING
200 READINGS (100 DIODES)
AT EACH VOLTAGE
CHARGE TIME IN MICROSECONDS
1200
1000
800
600
400
200
270 V.
280 V.
275 V.
285 V.
290 V.
295 V.
270 VOLTS
275 VOLTS
290 V
280 VOLTS
285 VOLTS
295 VOLTS
80
82
84
86
88
90
92
94
96
98
99
100
99.5
PERCENT PASSING

FIGURE 12

CONFIDENTIAL
NAVORD Report 2784



CONFIDENTIAL
SECURITY INFORMATION

FIGURE 13

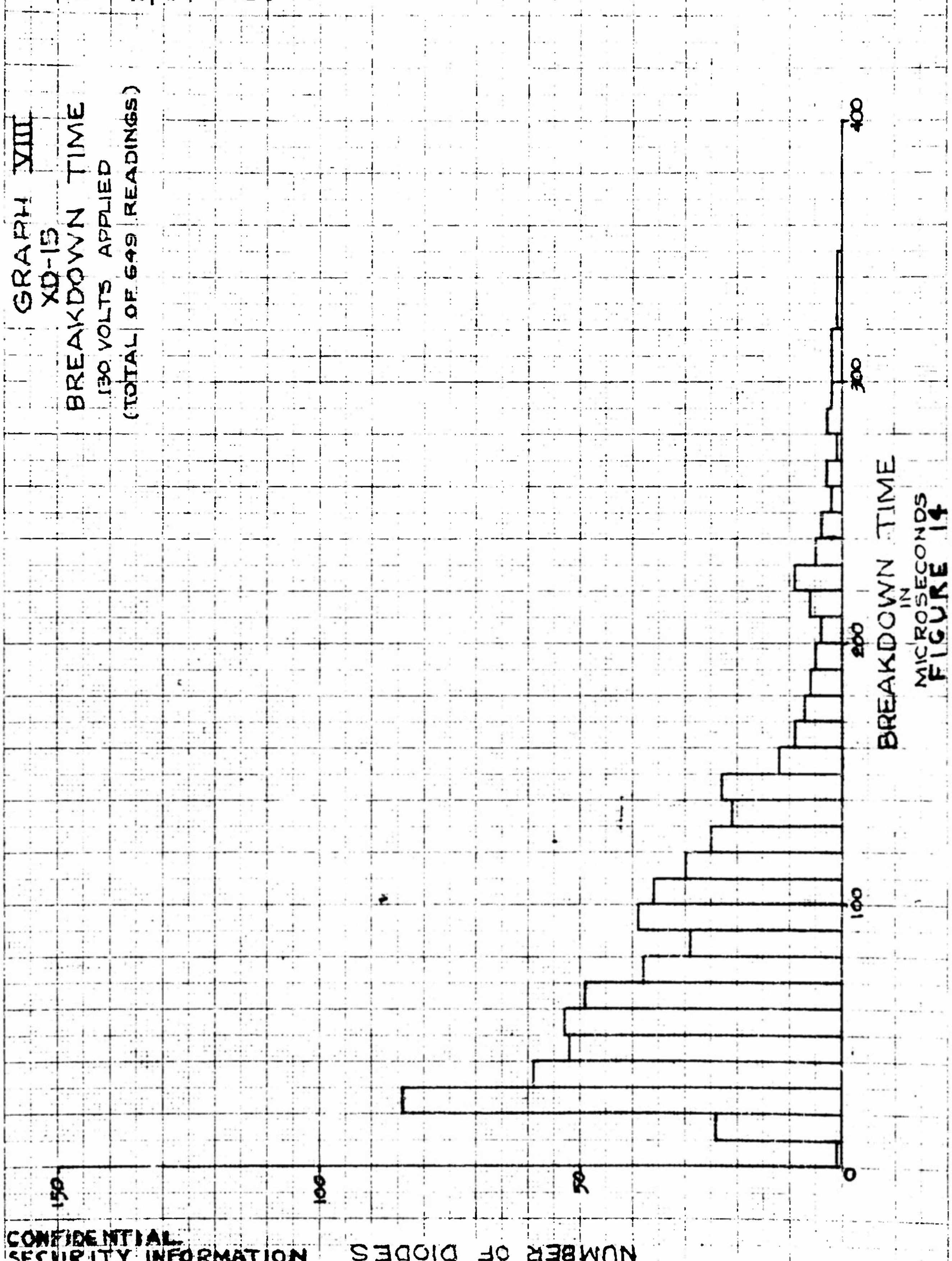

GRAPH VIII
XD-15
BREAKDOWN TIME
130 VOLTS APPLIED
(TOTAL OF 649 READINGS)
0
100
200
300
400
BREAKDOWN TIME IN MICROSECONDS
0
50
100
150
NUMBER OF DIODES

FIGURE 14

CONFIDENTIAL
NAVORD Report 2784

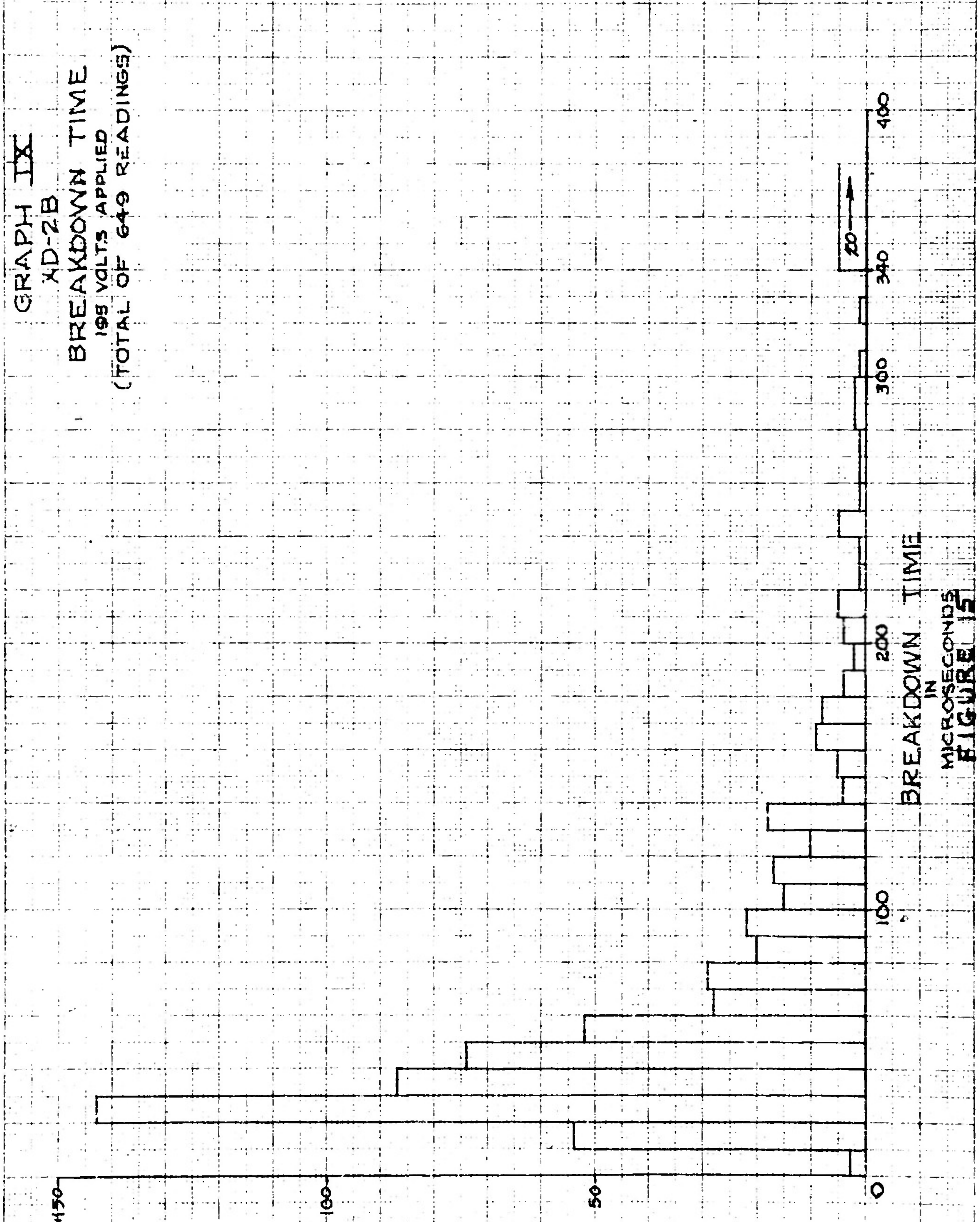


FIGURE 15

CONFIDENTIAL
SECURITY INFORMATION

CONFIDENTIAL
NAVORD Report 2784

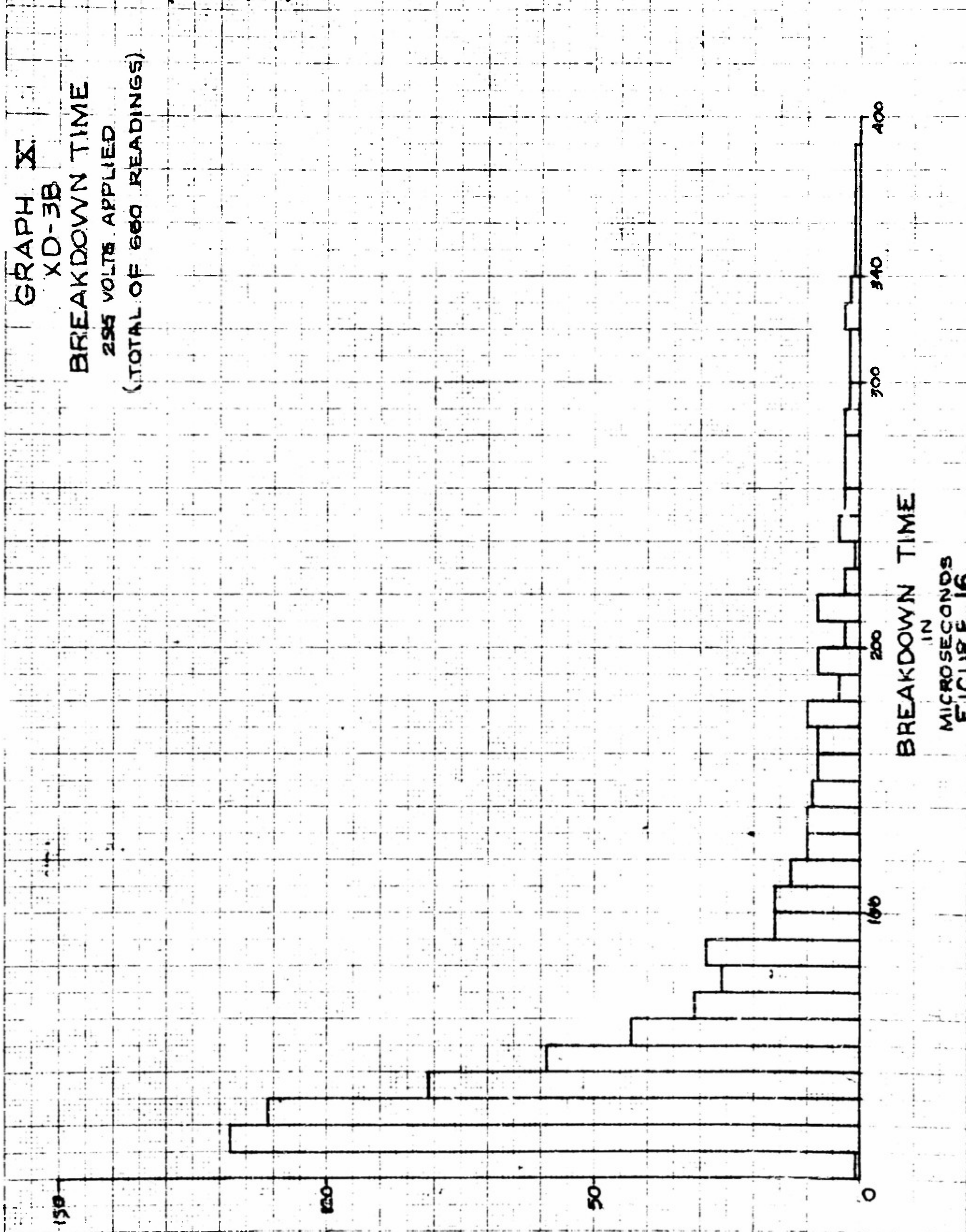


FIGURE 16

CONFIDENTIAL
SECURITY INFORMATION

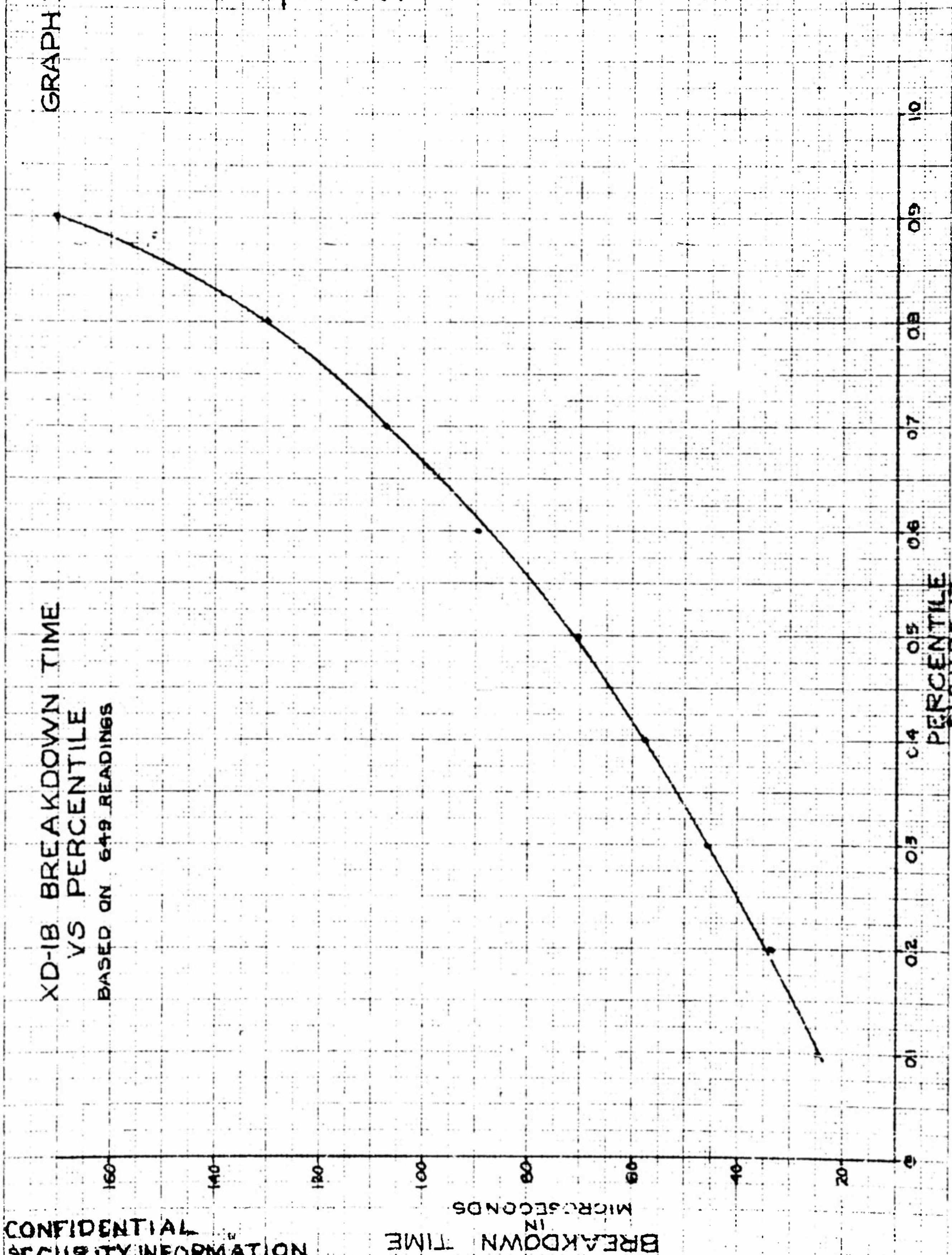

GRAPH XI
XD-1B BREAKDOWN TIME
VS PERCENTILE
BASED ON 649 READINGS
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PERCENTILE
160
140
120
100
80
60
40
20
BREAKDOWN TIME
IN
MICROSECONDS

FIGURE 17

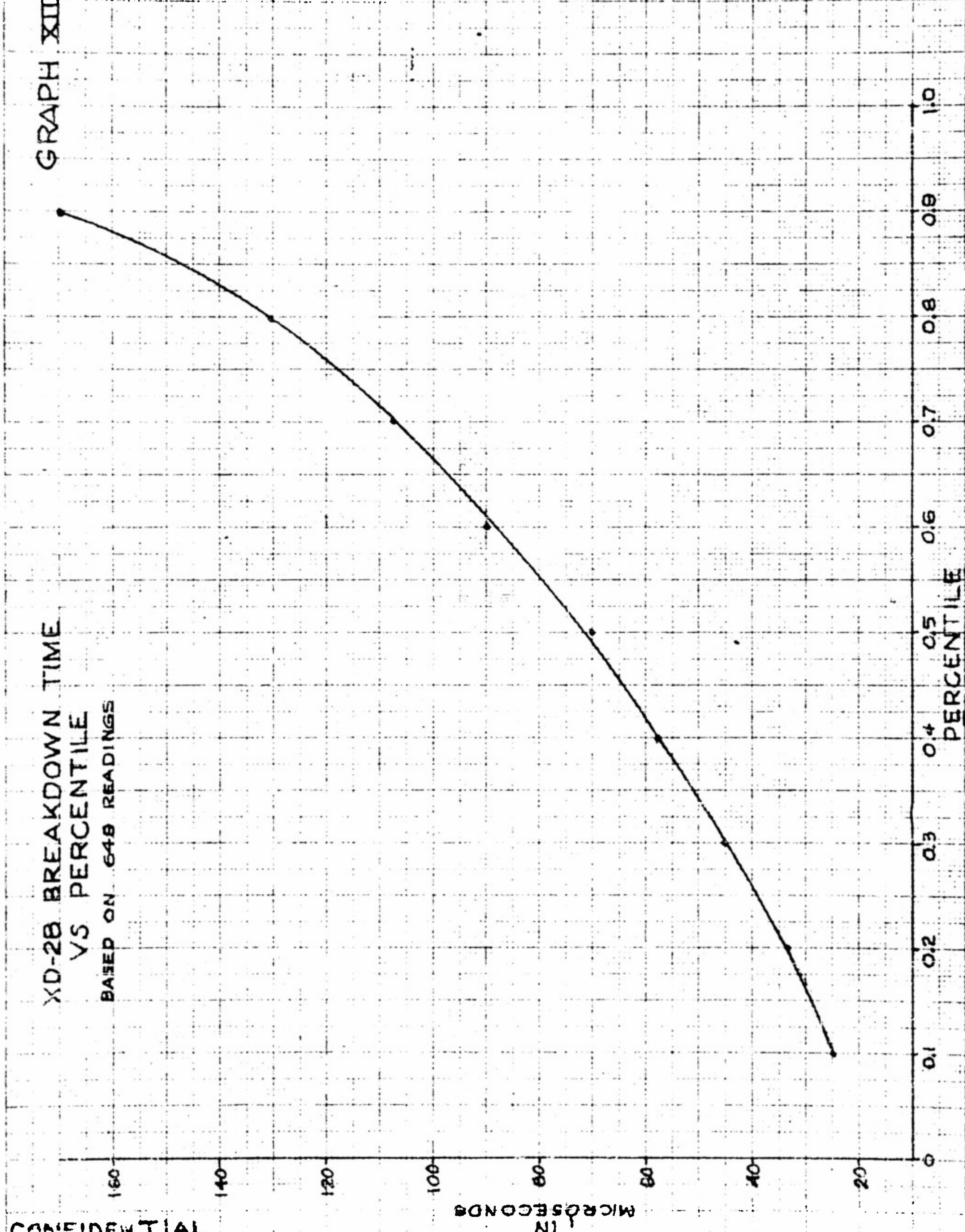

GRAPH XII
XD-2B BREAKDOWN TIME
VS PERCENTILE
BASED ON 648 READINGS
PERCENTILE
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
BREAKDOWN TIME
IN
MICROSECONDS
20
40
60
80
100
120
140
160

FIGURE 18

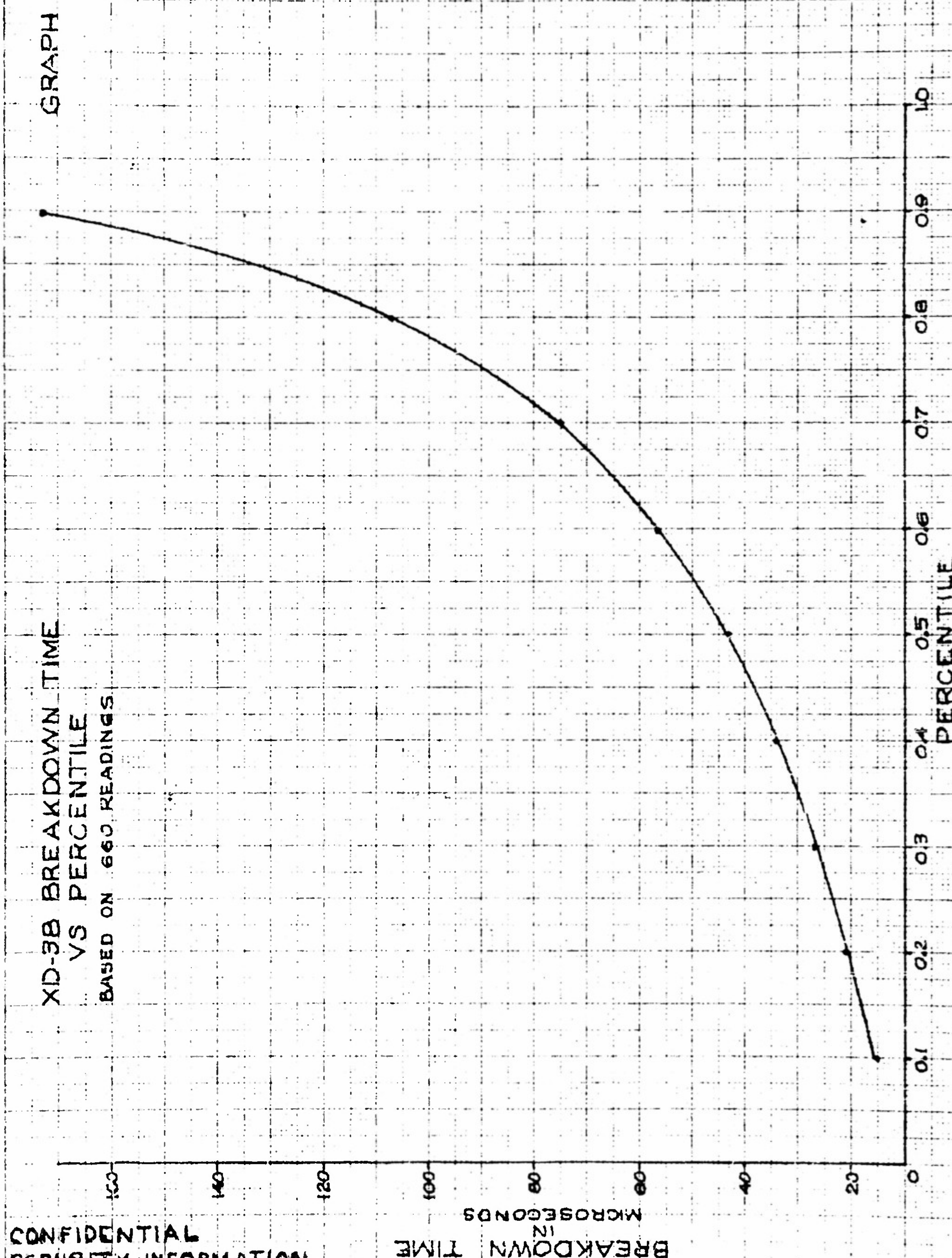

GRAPH XIII
XD-3B BREAKDOWN TIME
VS PERCENTILE
BASED ON 660 READINGS
PERCENTILE
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
20
40
60
80
100
120
140
160
BREAKDOWN TIME
IN
MICROSECONDS

FIGURE 19

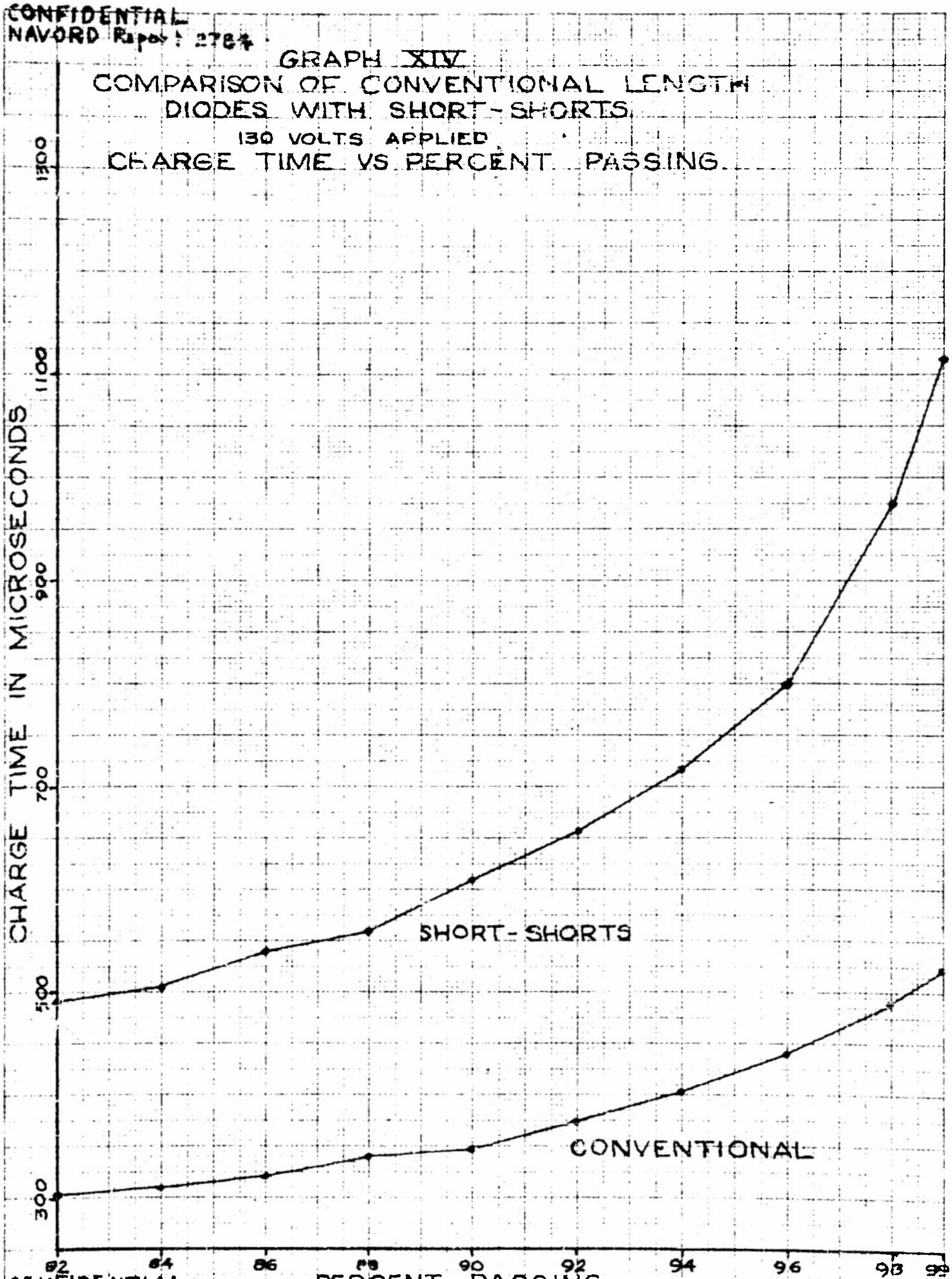

GRAPH XIV
COMPARISON OF CONVENTIONAL LENGTH DIODES WITH SHORT-SHORTS
130 VOLTS APPLIED
CHARGE TIME VS PERCENT PASSING.
CHARGE TIME IN MICROSECONDS
1300
1100
900
700
500
300
SHORT-SHORTS
CONVENTIONAL
82
84
86
88
90
92
94
96
98
99
PERCENT PASSING

FIGURE 20

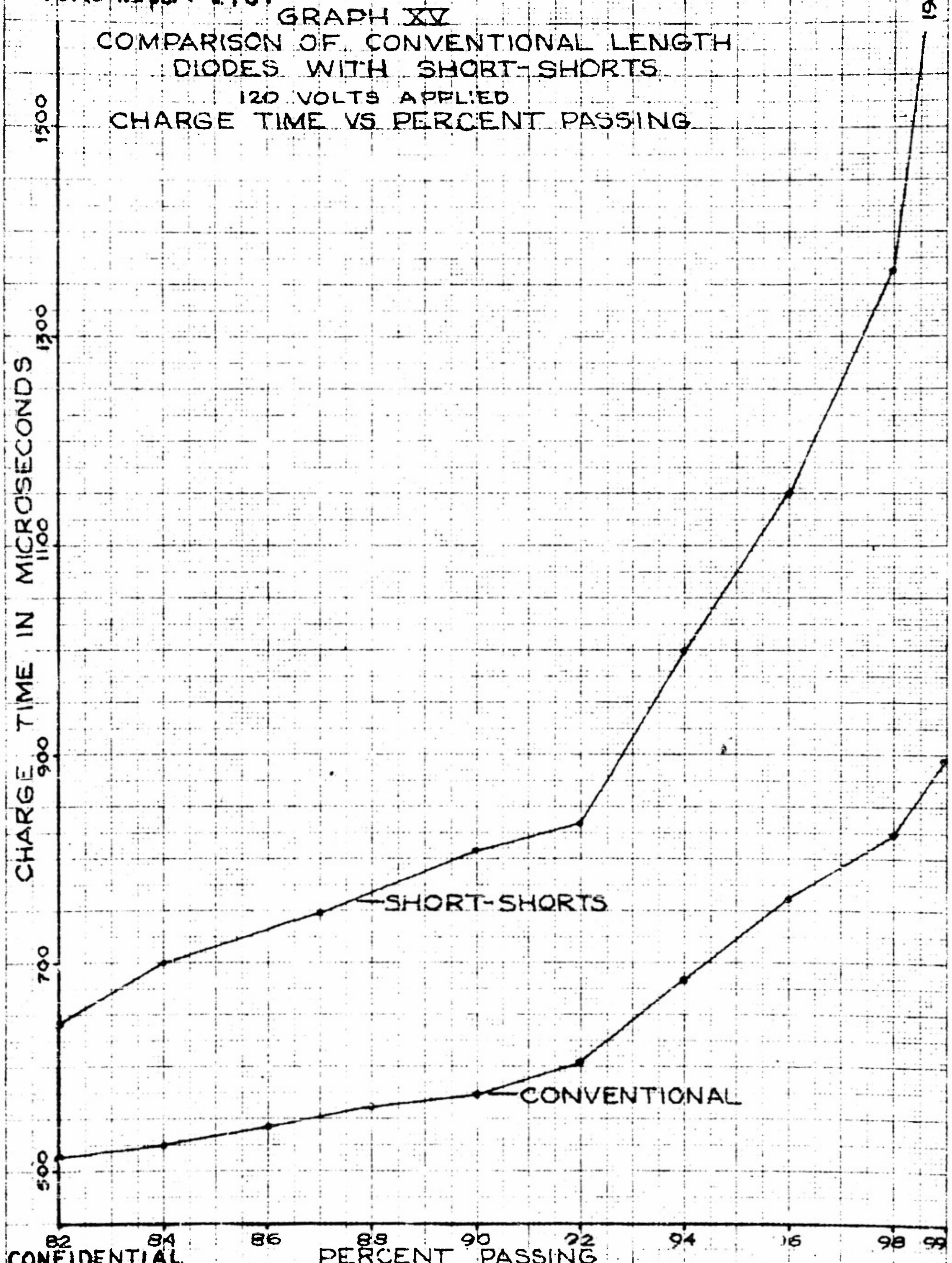
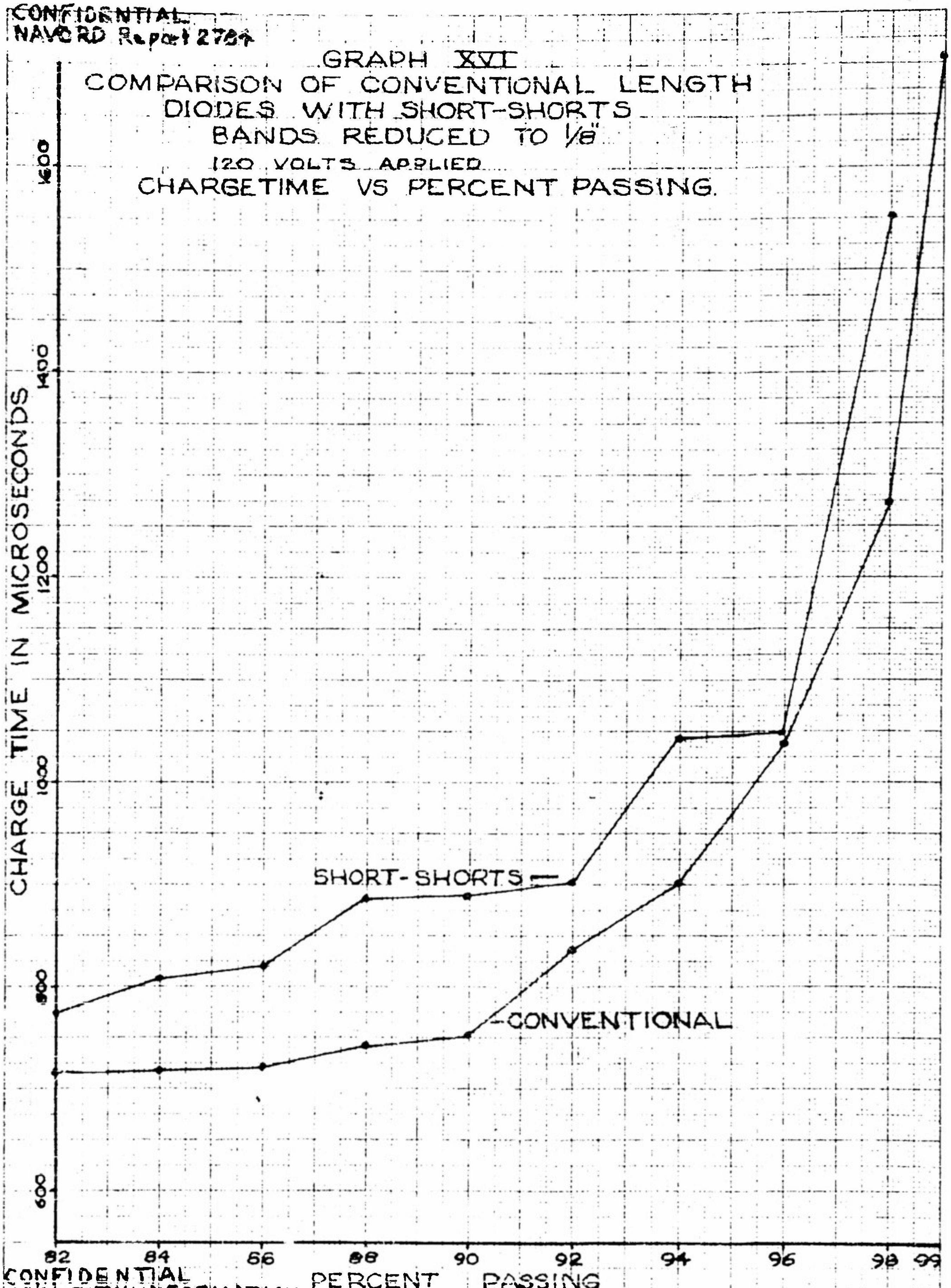

GRAPH XV
COMPARISON OF CONVENTIONAL LENGTH
DIODES WITH SHORT-SHORTS
120 VOLTS APPLIED
CHARGE TIME VS PERCENT PASSING
CHARGE TIME IN MICROSECONDS
1500
1300
1100
900
700
500
1948
SHORT-SHORTS
CONVENTIONAL
82
84
86
88
90
92
94
96
98
99
PERCENT PASSING

FIGURE 21

CONFIDENTIAL
NAVORD Report 2784



CONFIDENTIAL
SECURITY INFORMATION

FIGURE 22